# PROGRESS TOWARD □ LIMITS FOR COMPACT STELLARATORS


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**and**

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**ARIES-CS Project Meeting**
**University of California, San Diego**
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# SUMMARY STATUS OF ARIES-CS EQUILIBRIUM AND STABILITY ANALYSIS

- **Equilibrium and stability results for the ARIES-CS study with results from Paul Garabedian presented at the EPS Meeting in June 2004:**
  - **General (but not universal) agreement on conclusions for meaning of MHD stability limits in stellarators**

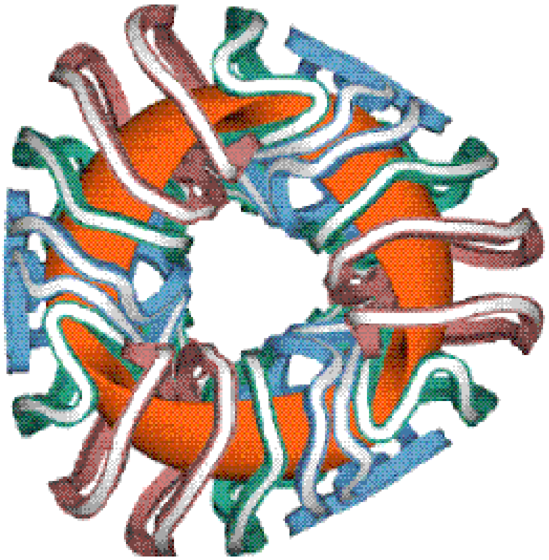
- **Previous failure in TERPSICHORE code due to memory problems on Linux platforms was resolved (W.A. Cooper):**
  - **Previously limited to maximum radial mesh of 97 flux surfaces**
  - **Limitation on mesh is now fully circumvented by rewriting code using F90 modules and dynamic array allocation**

- **Equilibria with increased resolution obtained:**
  - **Radial mesh increased from 97 to 149 surfaces**
    - **Scaled NCSX with $\beta$ = 5.7% and 8.3% and MHH2 with $\beta$ = 6.92%**
  - **Higher mesh stability calculations confirmed previous conclusions:**
    - **$\beta$ limit for scaled NCSX and MHH2 equilibria ~ 6%**

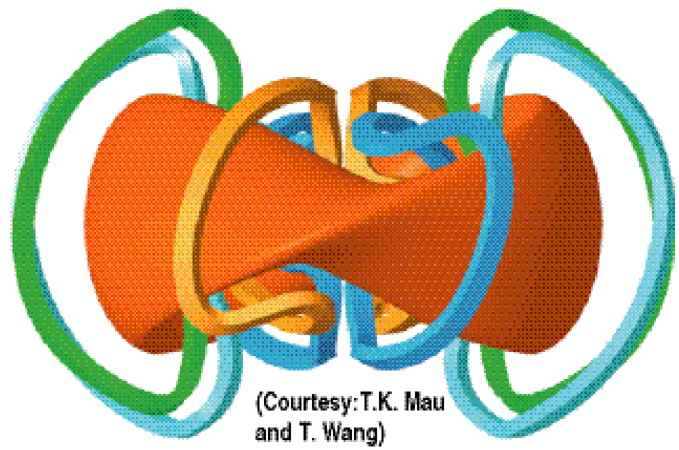
- **Previous restriction on close wall positions was resolved:**
  - **New parameter to allow some toroidal variation in the conformal wall can be chosen to prevent wall from locally becoming too close**
  - **Some experimentation is required**

# MODULAR COIL CONFIGURATIONS FOR THREE AND TWO FIELD PERIOD CONFIGURATIONS

- Scaled NCSX: Eighteen coil design



- MHH2: Eight moderately twisted modular coil design




- Good quasi-axisymmetry:
  - Asymmetric $B_{mn}$ terms are same order as a typical tokamak with ripple from toroidal coils or helical excursion of magnetic axis from MHD instability

# COMPACT STELLARATOR EQUILIBRIUM AND LINEAR IDEAL MHD STABILITY ANALYSIS

- Scaled-up NCSX three-field period equilibrium from VMEC:
  - Reference equilibrium:

    $<\beta> = 4.1\%$

| V ($m^3$) | R(m) | a(m) | A | <B>(T) |
|---|---|---|---|---|
| 556.5 | 8.25 | 1.85 | 4.47 | 4.47 |

- MHH2 two-field period equilibrium from VMEC:
  - Reference equilibrium:

    $<\beta> = 4.52\%$

| V ($m^3$) | R(m) | a(m) | A | <B>(T) |
|---|---|---|---|---|
| | | | | |

- Sequence of equilibria with increasing β by uniformly scaling pressure profile:
  - Volume, Average major and minor radius and vacuum field held fixed
  - Shape of the outer plasma boundary fixed: no coils specified
  - ι profile adjusted to force average current density to vanish as β increases

    ⇒ Bootstrap current not self consistently calculated
  - Magnetic axis ($R_m(0)$: major radius of magnetic axis at a single toroidal plane) shifts outward as β increases

- Scaled NCSX sequence

| | | | | | |
|---|---|---|---|---|---|
| $<\beta>(\%)$ | 4.1 | 4.9 | 5.7 | 7.0 | 8.3 |
| $R_m(0)$ (m) | 9.20 | 9.21 | 9.22 | 9.24 | 9.26 |

- MHH2 sequence

| | | | |
|---|---|---|---|
| $<\beta>(\%)$ | 4.52 | 5.71 | 6.92 |
| $R_m(0)$ (m) | | | |

# SUMMARY OF EPS 2004 AND LAUSANNE TRIP

- **Presented results from the ARIES Compact Stellarator stability study performed by GA for the ARIES group.**
  - **Combined with contributions from Paul Garabedian (NYU)**
  - **Paper was quite well received**
  - **The presentation can also be downloaded from the following URL:**
    **http://fusion.gat.com/~turnbull/Files_for_Download/EPS_2004_ARIES-CS_Project.pdf**
- **The major thesis of the work, was that:**
  - **Linear stability calculations for stellarator designs need to be benchmarked properly against experiments using reconstructed equilibria, and**
  - **Calculated limits then need to be interpreted according to mode type as is the case for tokamaks**

**Otherwise, linear calculations for stellarators yield unrealistically low □ limits that actually appear to be well exceeded by present experiments**

- **This thesis was largely (though not yet universally) accepted**
- **Paul Garabedian presented complementary results showing his approach predicts nonlinear □ limits that agree better with experimental results**
- **Dr. Sakakibara (JIFS) presented results on MHD stability of LHD**
  - **Conclusion that they need to measure □profile was identical to mine**

# CONVERGENCE TESTS FOR THREE-PERIOD SCALED UP NCSX EQUILIBRIA CONFIRM PREVIOUS STABILITY RESULTS

- **Radial mesh: 49, 97, 149, and 197 surfaces for two cases:**
  - **$\beta$ = 5.7% and $\beta$ = 8.3%**
- **Ideal n=1 mode family stability is sensitive to mesh:**
  - **Squared growth rate $\omega^2$ vs $\beta$: $\omega^2 > 0 \Rightarrow$ stable / $\omega^2 < 0 \Rightarrow$ unstable**

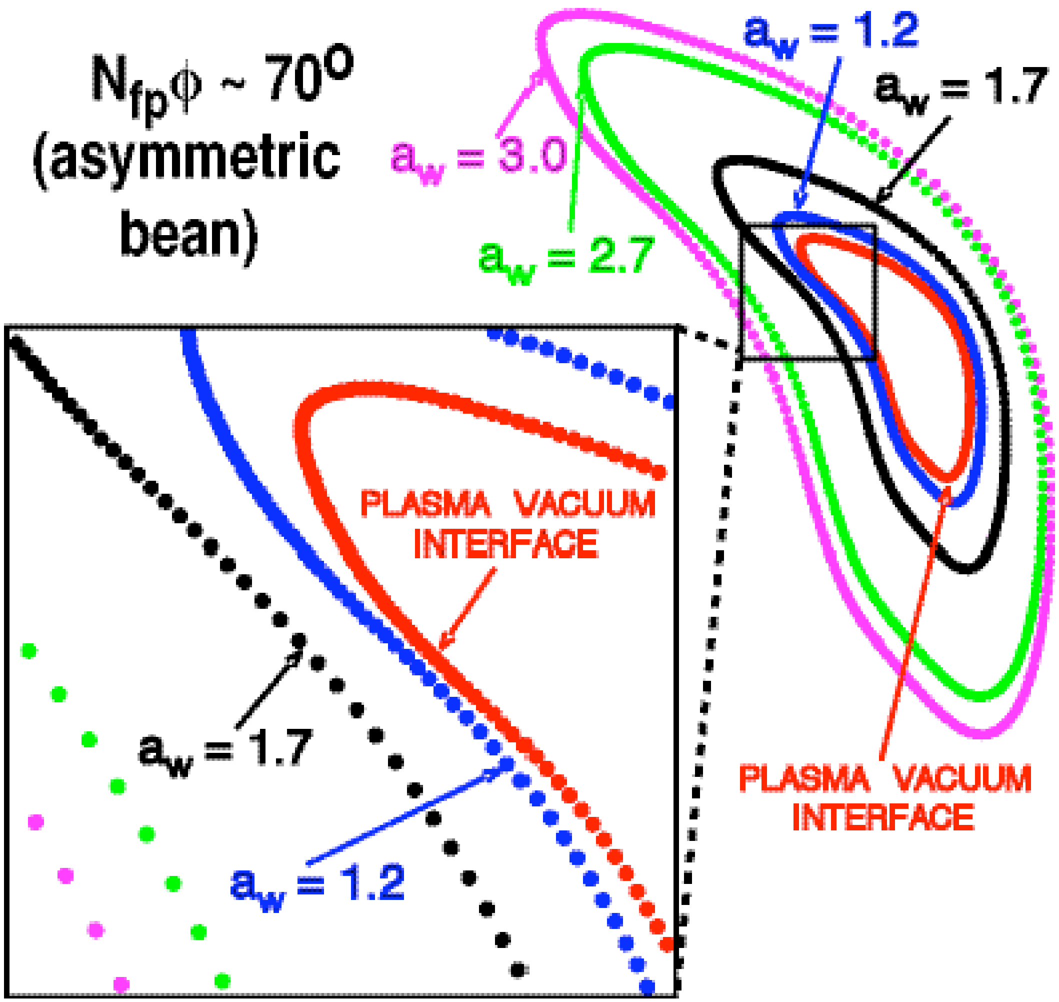
**Scaled NCSX Configuration:**

| $\beta$ | Wall position | 49 surfaces | 97 surfaces | 149 surfaces | 197 surfaces |
|---|---|---|---|---|---|
| 5.7% | 2.0 | +1.86703E-04 | +4.44782E-05 | +1.95716E-05 | |
| 5.7% | 2.5 | +1.86691E-04 | +4.44763E-05 | +2.05464E-05 | |
| 8.3% | 2.5 | -1.63785E-02 | -1.03321E-02 | -1.18285E-02 | -1.00748E-02 |

**MHH2 Configuration:**

| $\beta$ | Wall position | 49 surfaces | 97 surfaces | 149 surfaces | 197 surfaces |
|---|---|---|---|---|---|
| 6.92% | 3.0 | -7.15261E-05 | -6.61238E-06 | -4.38885E-06 | |

# PREVIOUSLY IDENTIFIED CAUSE OF FAILURE IN STABILITY CALCULATION FOR CLOSE WALL

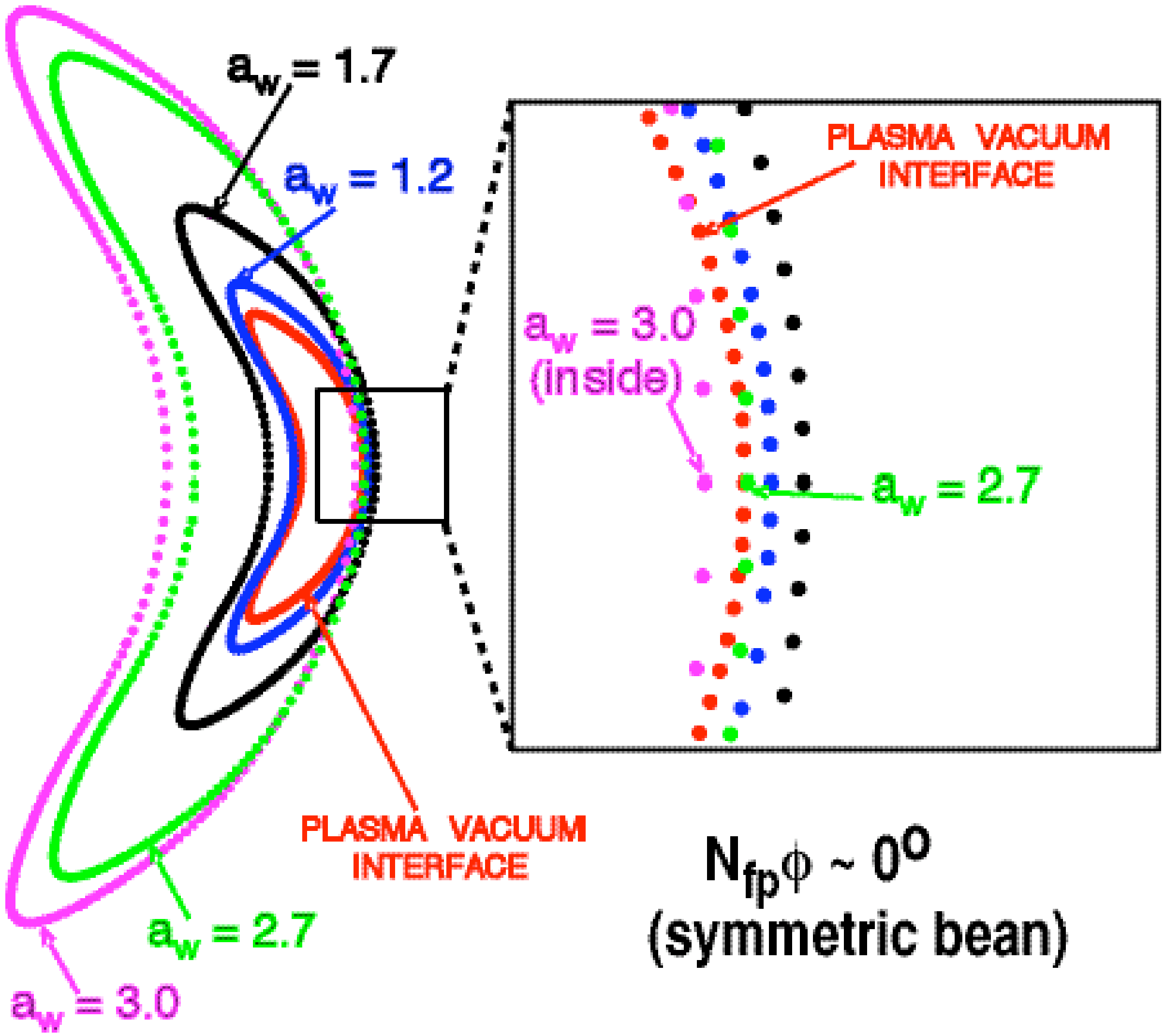



**For $a_w < 1.7$:**

**Wall approaches plasma surface at a point on inboard side at one toroidal plane**

**Vacuum calculation fails due to logarithmic singularity as plasma-wall distance locally vanishes**

# PREVIOUSLY IDENTIFIED CAUSE OF FAILURE IN STABILITY CALCULATION FOR DISTANT WALL

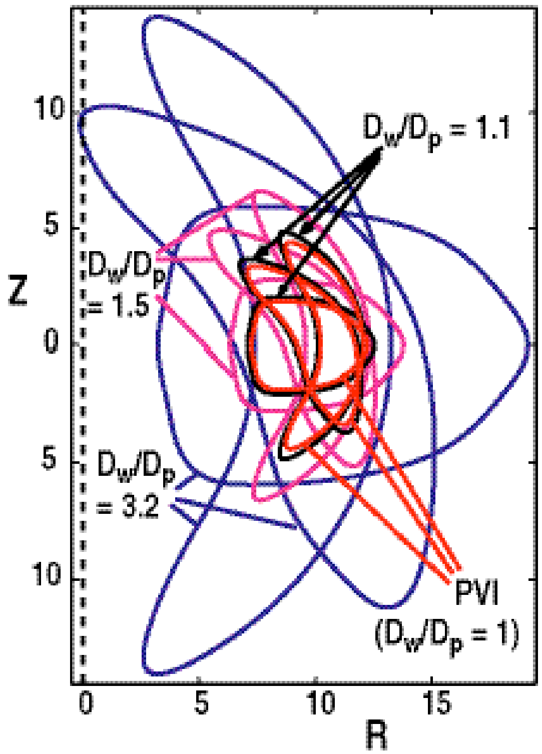



**Increasing $a_w$:**
**Outboard wall begins to move inward slightly at toroidal planes where plasma is bean shaped and up-down symmetric**

**For $a_w > 2.7$:**
**Wall cuts plasma-vacuum interface at point on outboard midplane**

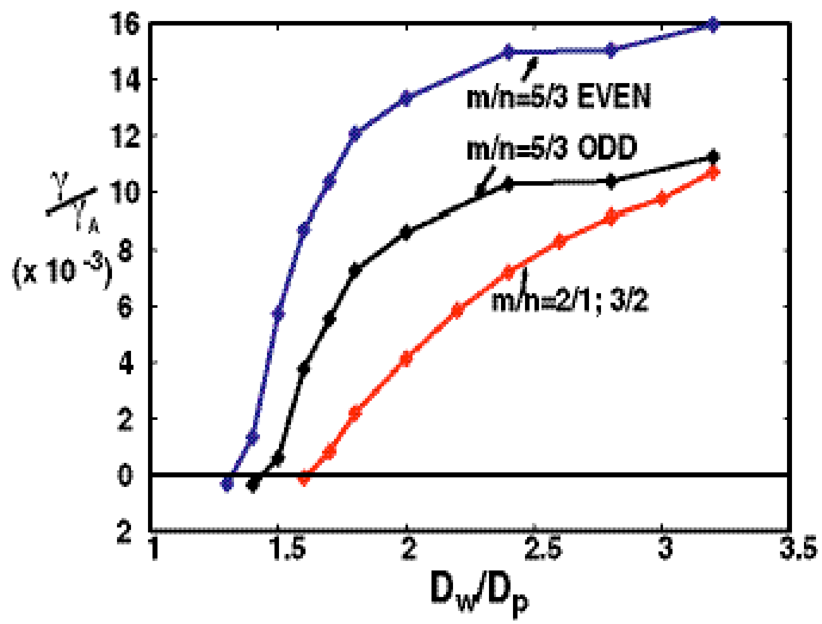
# CONFORMAL WALLS FOR COMPACT STELLARATOR CONFIGURATIONS CAN NOW APPROACH PLASMA SURFACE

Constructed conformal walls for NCSX equilibrium at several toroidal locations corresponding to different scale factors




## NCSX Equilibrium

Dependence of normalized growth rate for various modes on conformal wall position $D_w$ normalized to the plasma boundary radius $D_p$



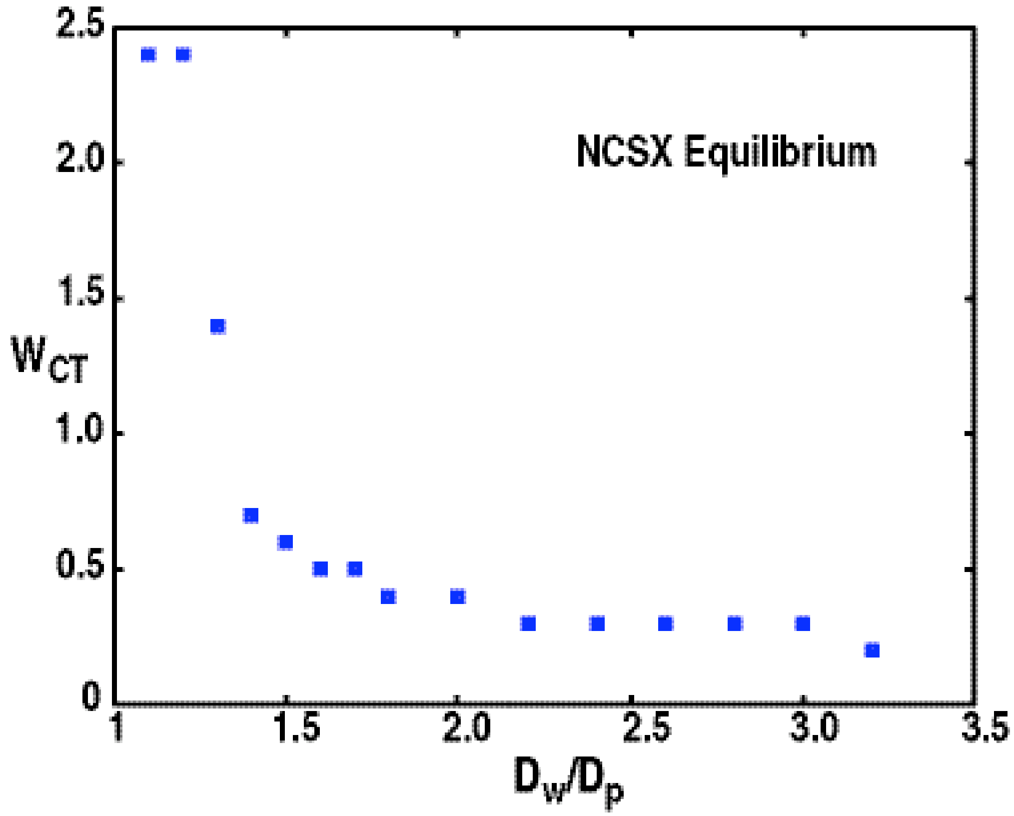

- **Growth rates decay smoothly as wall is brought inward**



GENERAL ATOMICS

# NEW PARAMETER $W_{CT}$ ADJUSTS TOROIDAL VARIATION OF CONFORMAL WALLS

- **Parameter $W_{CT}$ requires adjustment as wall approaches plasma**




- **Experimentation for finding $W_{CT}$ in ARIES-CS is in progress:**
  - **Scaled NCSX case finds similar values down to wall with $D_w/D_p = 1.1$**
  - **Higher mesh cases find much larger range in acceptable $W_{CT}$ values**
  - **MHH2 case is underway but so far successful**

# WALL POSITION TAKEN DOWN TO 1.1 TIMES PLASMA MINOR RADIUS FOR BOTH SCALED NCSX AND MHH2 CONFIGURATIONS

**Squared growth rate □² vs □: □² > 0 □ stable / □² < 0 □ unstable:**

| □ (Scaled NCSX) | Wall position | Rayleigh Quotient (149 surfaces) | □ (MHH2) | Wall position | Rayleigh Quotient (97 surfaces) |
|---|---|---|---|---|---|
| 8.3% | 3.0 | -1.46121E-02 | 6.92% | 3.0 | -6.61238E-06 |
| 8.3% | 2.5 | -1.18285E-02 | 6.92% | 2.5 | -6.61670E-06 |
| 8.3% | 2.0 | -2.81748E-03 | 6.92% | 2.0 | -6.60531E-06 |
| 8.3% | 1.7 | +3.29816E-05 | 6.92% | 1.7 | -6.60492E-06 |
| 8.3% | 1.5 | +3.46380E-05 | 6.92% | 1.5 | -6.59681E-06 |
| 8.3% | 1.4 | +3.36925E-05 | 6.92% | 1.4 | -6.59070E-06 |
| 8.3% | 1.3 | +3.25127E-05 | 6.92% | 1.3 | -6.57594E-06 |
| 8.3% | 1.2 | +3.18000E-05 | 6.92% | 1.2 | -6.55346E-06 |
| 8.3% | 1.1 | +3.18872E-05 | 6.92% | 1.1 | NOT YET |

# PROGRESS SUMMARY: PLANNED STABILITY ANALYSIS: 2004

| TASK | STATUS | COMMENTS |
|---|---|---|
| Reconstruct base 3-Field Period equilibrium | Completed June 2004 | Reconstruct increasing □ NCSX-like equilibrium sequence using VMEC |
| Stability Calculation of revised 3-Field Period case using Terpsichore | Completed November 2004 | Test convergence, □ limit, and sensitivity: The prior problem with large meshes was corrected. Convergence studies are complete |
| Reconstruct 2 field period equilibrium or other variant | Completed June 2004 | Reconstructed PPPL version of MHH2: Two-field period variant from Paul Garabedian. |
| Stability Calculation of 2-Field Period case using Terpsichore | In Progress September 2004 | Test convergence, □ limit, and sensitivity: Convergence studies are in progress |
| Fix Wall Construction for Close Walls | Completed August 2004 | Extract logarithmic singularity carefully: This was solved by A.W. Cooper with changes to the wall construction routines |
| Fix Wall Construction for Distant Walls | Deferred | Eliminate construction of negative radius wall points by forcing them to be small and positive |