# Coil Design Status for the QAS3_c10a Reference Plasma Configuration

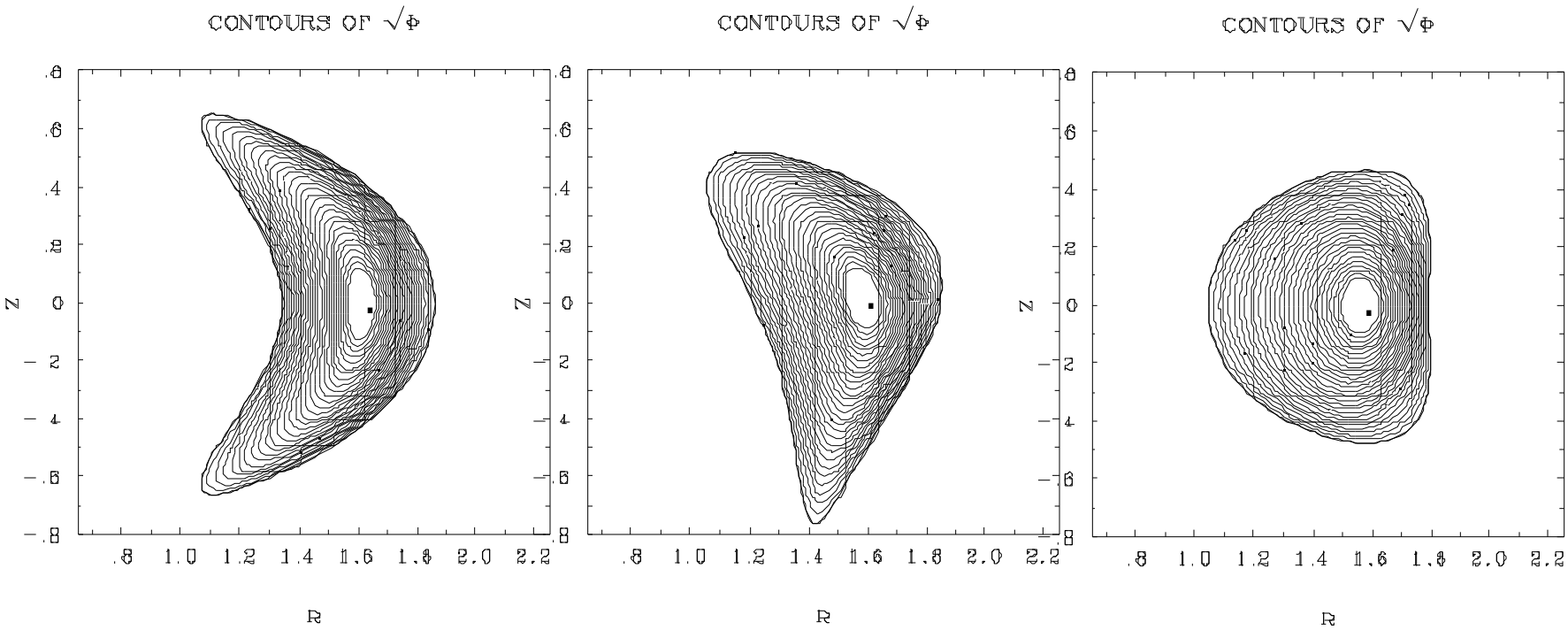
# Overview

- Plasma Reconstruction Issues
  - Current Sheets
  - Discrete Coils
- Surface Offset Scan
  - Current Density
  - Coil Complexity
- Coil Topology Scan
  - Variation of Ipol, Itor

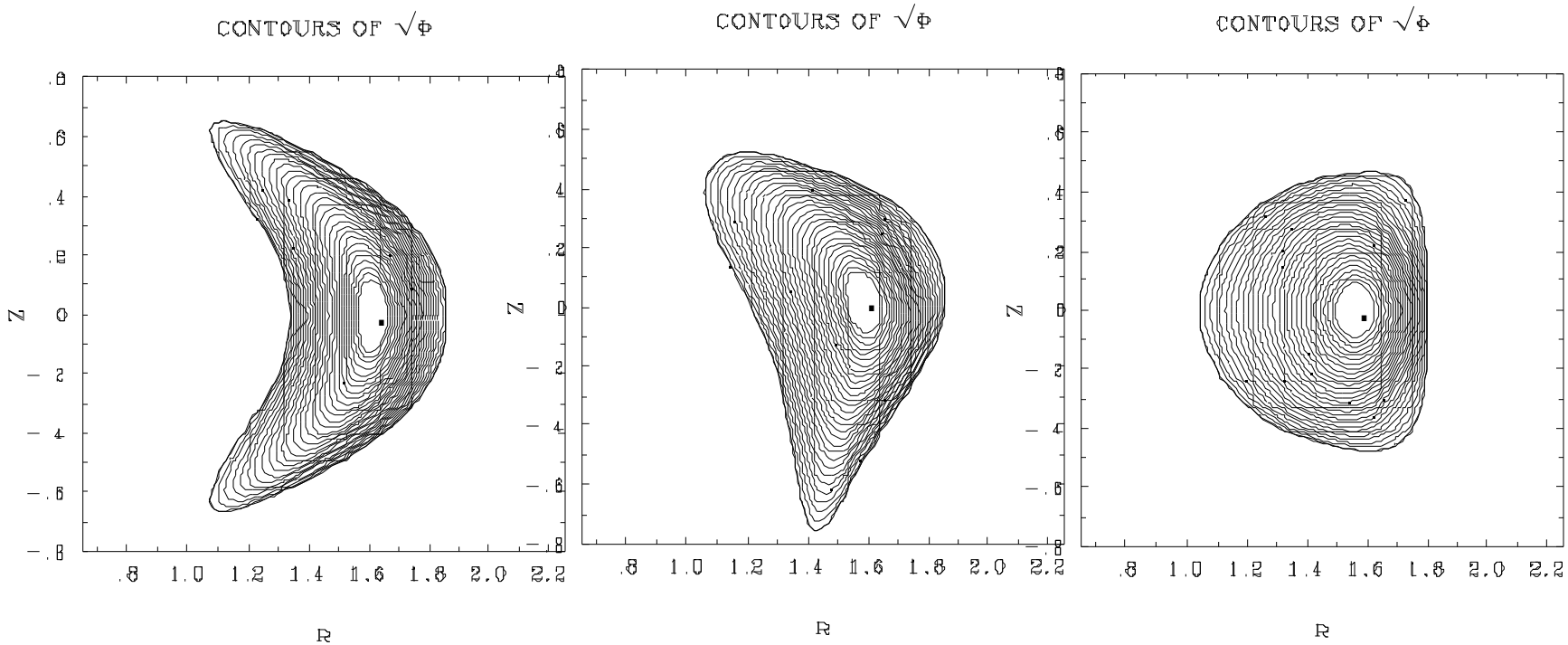
# Plasma Reconstruction Status

- Successfully reconstructed plasma from both saddle and helical current sheet solutions
  - Provides reassurance that Fix Boundary VMEC to Bnorm_code to NESCOIL to Free Boundary VMEC loop is working properly
  - Difficulty lies with coil discretization effects
- Reconstructed plasma using large number of discrete filament coils for modular, saddle and helical designs
  - Demonstrates that with large numbers of coils current sheet solution can be approached
  - However, the observed max coil to coil separation tolerable is less than coil surface offset (20cm). Needed to fully cover surface with coils.

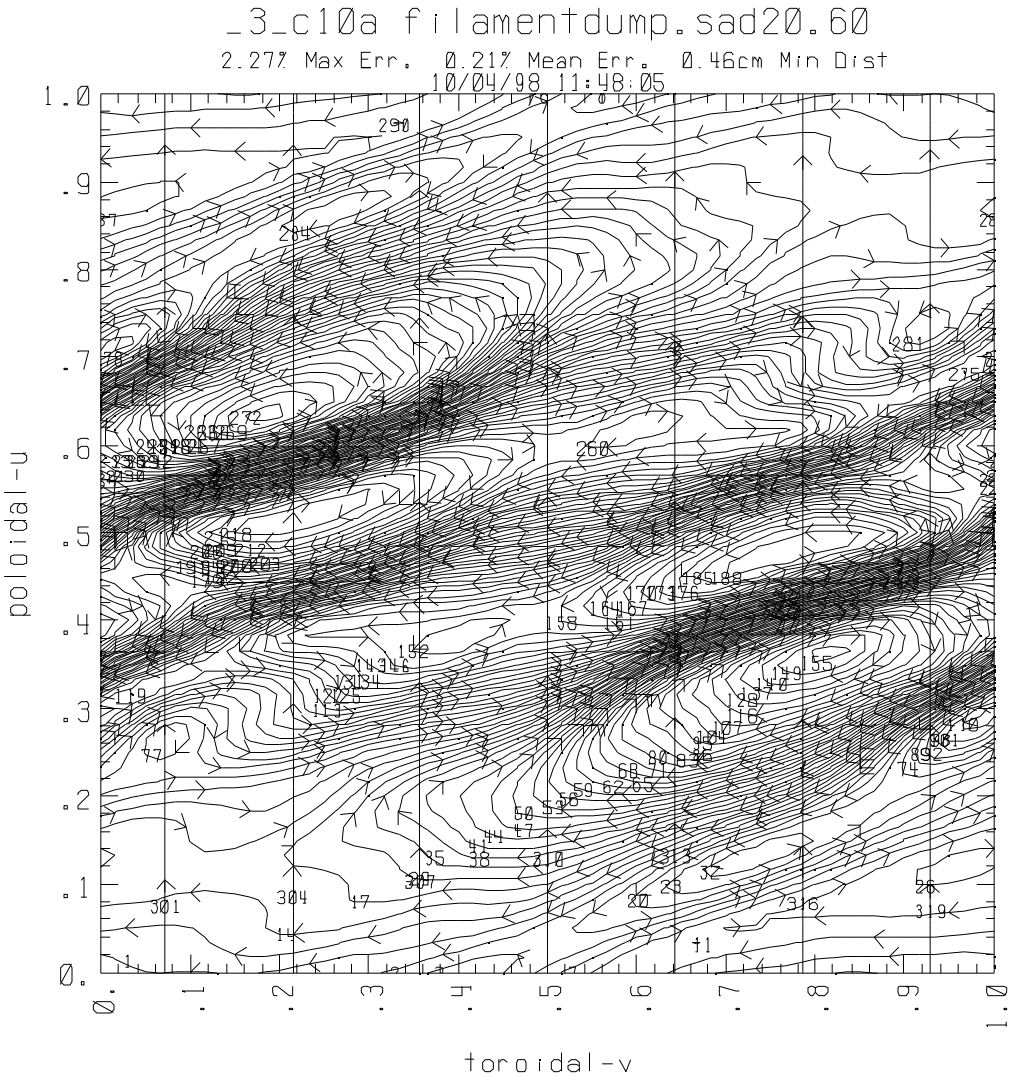
# Reference Fixed Boundary VMEC



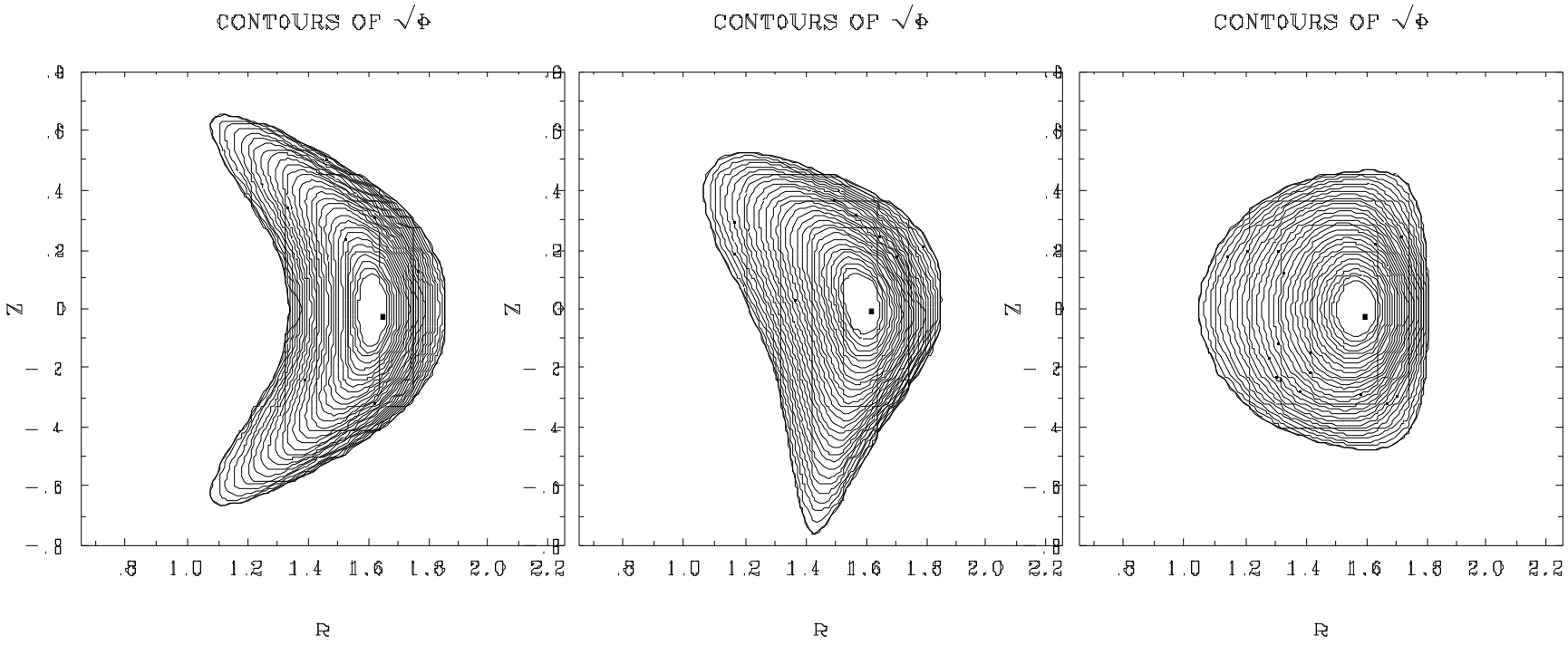
# Good Current Sheet Reconstruction



# Saddle Coils using 60 contour levels



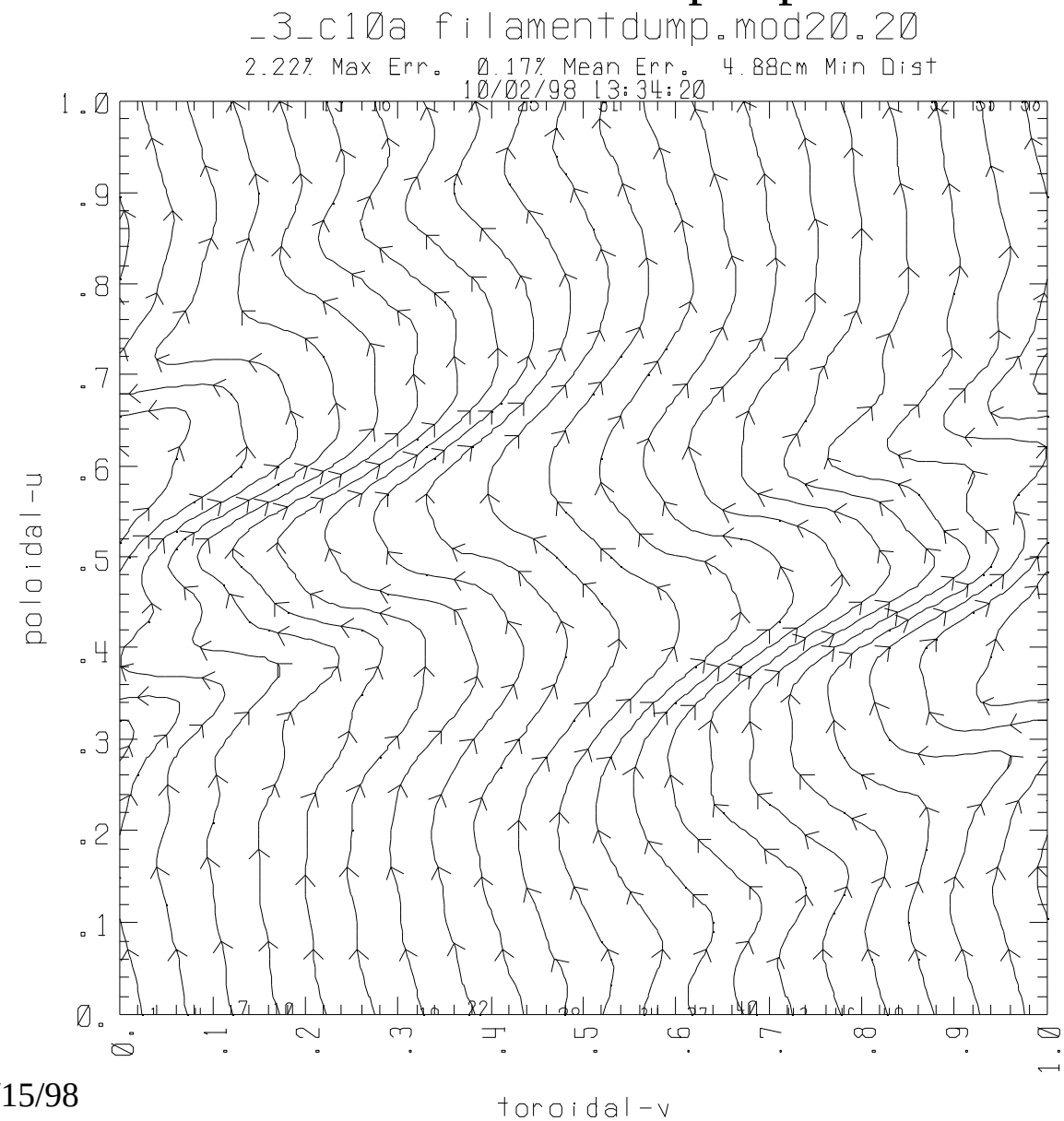
# Good reconstruction for Saddles with 60 contour levels



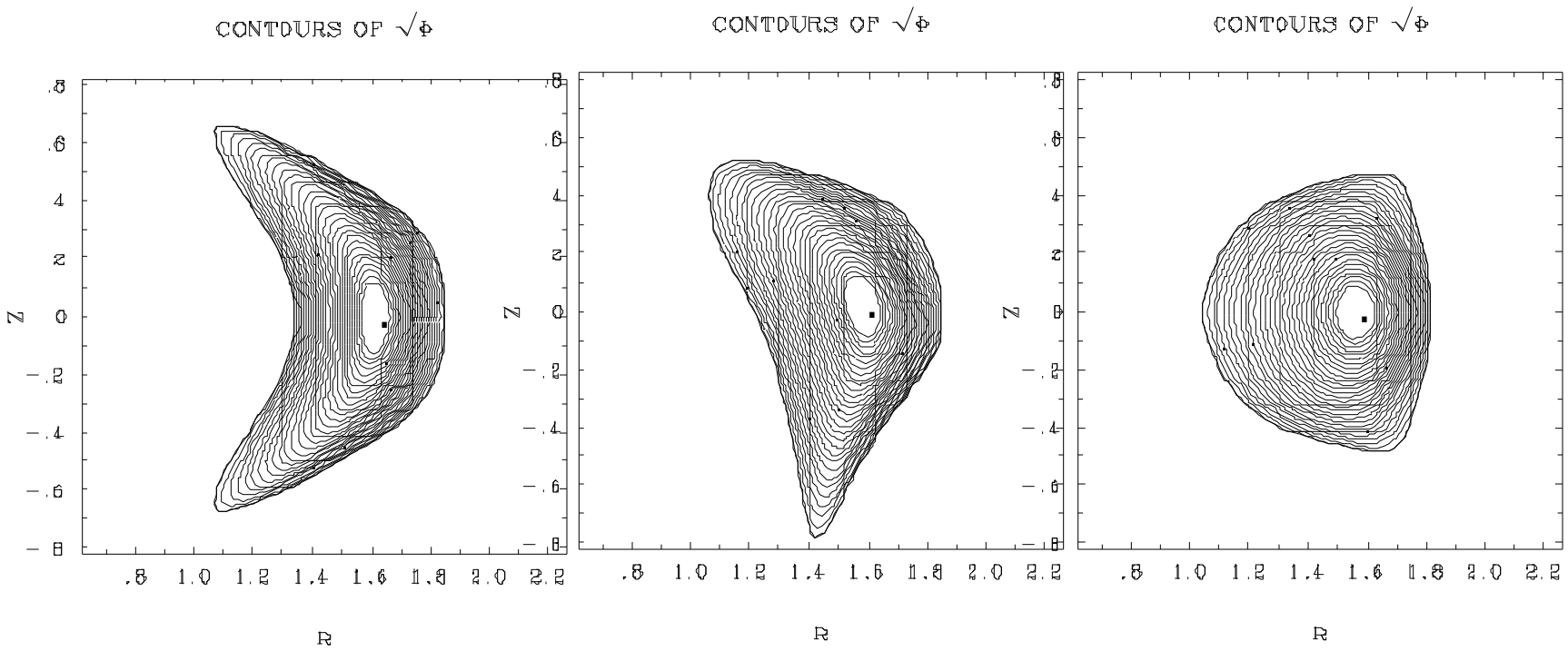
# Plasma Reconstruction Status, cont'd

- Using more reasonable numbers of coils has failed to reconstruct even in cases where errors are comparable to current sheet solution.
  - These are the max/mean errors coming out of standard NESCOIL
  - Need to investigate resonance errors (displacement) using tools presently under development.
  - Should also evaluate "fair" or even "poor" reconstructions for qas and stability properties to help define "how good is good enough"

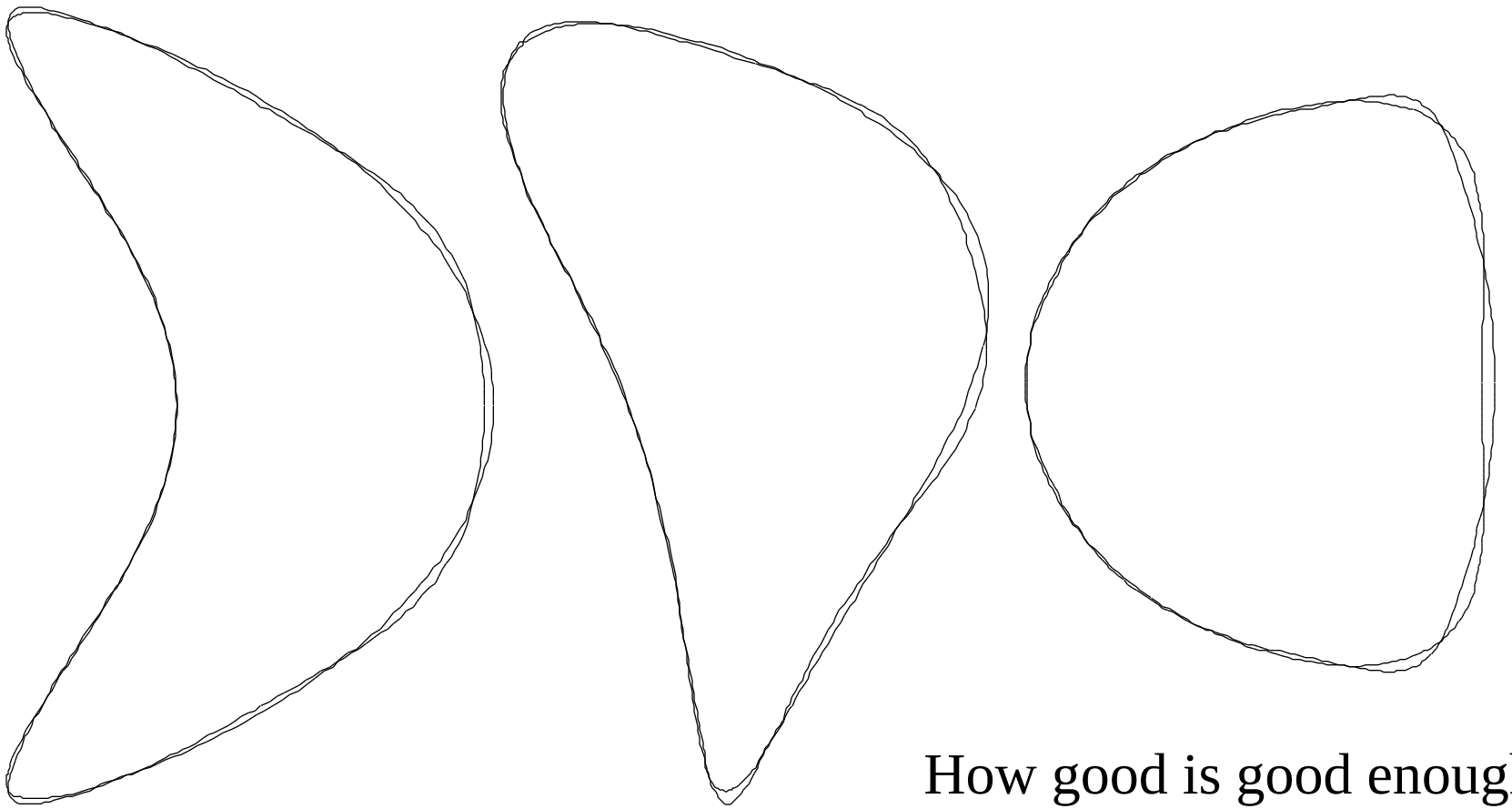
# 20 modular coils per period



# “Fair” Reconstruction with 20 Modular Coils per Period

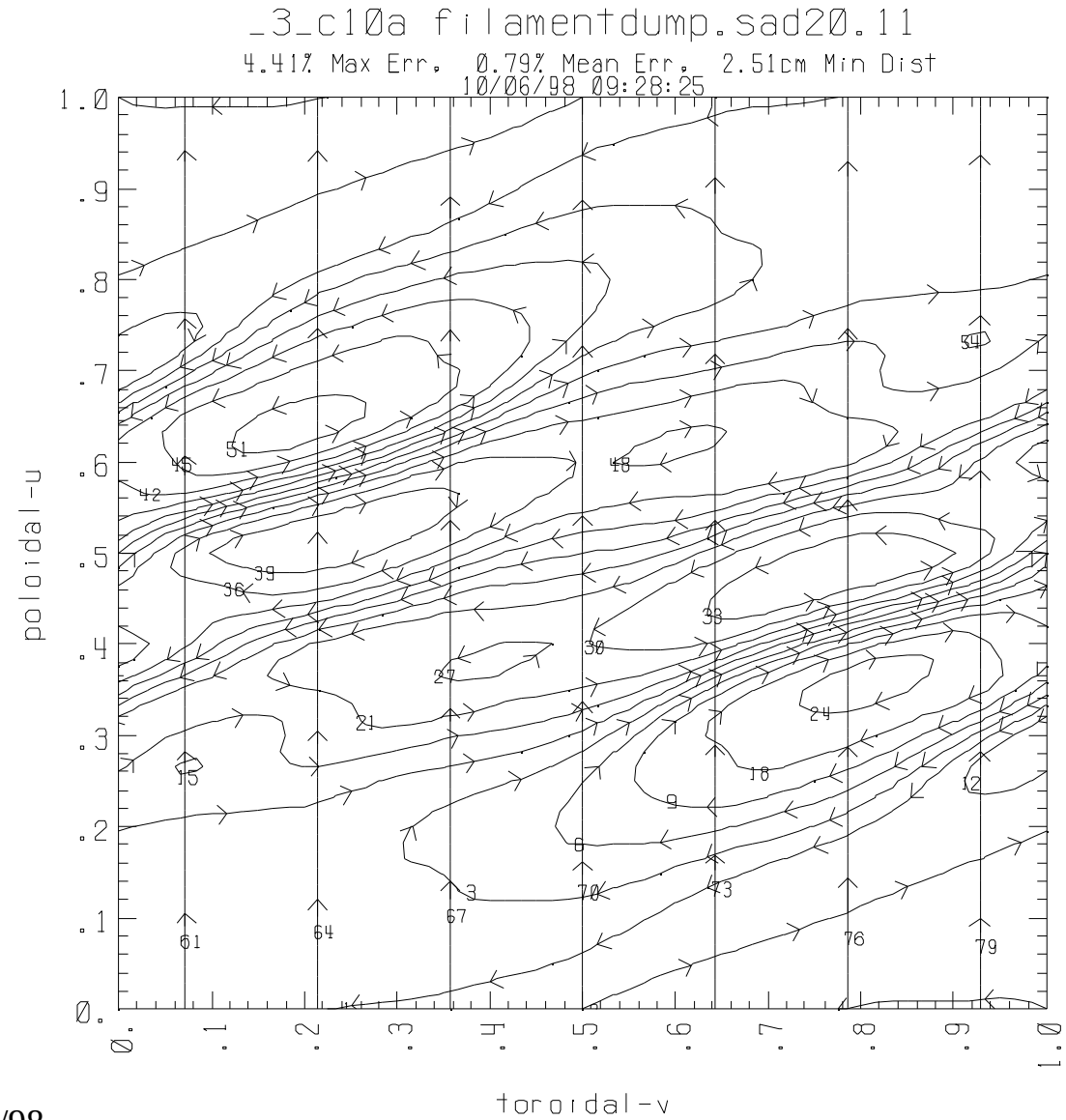


# “Fair” Reconstruction with 20 Modular Coils per Period Overlaid with Fixed Boundary

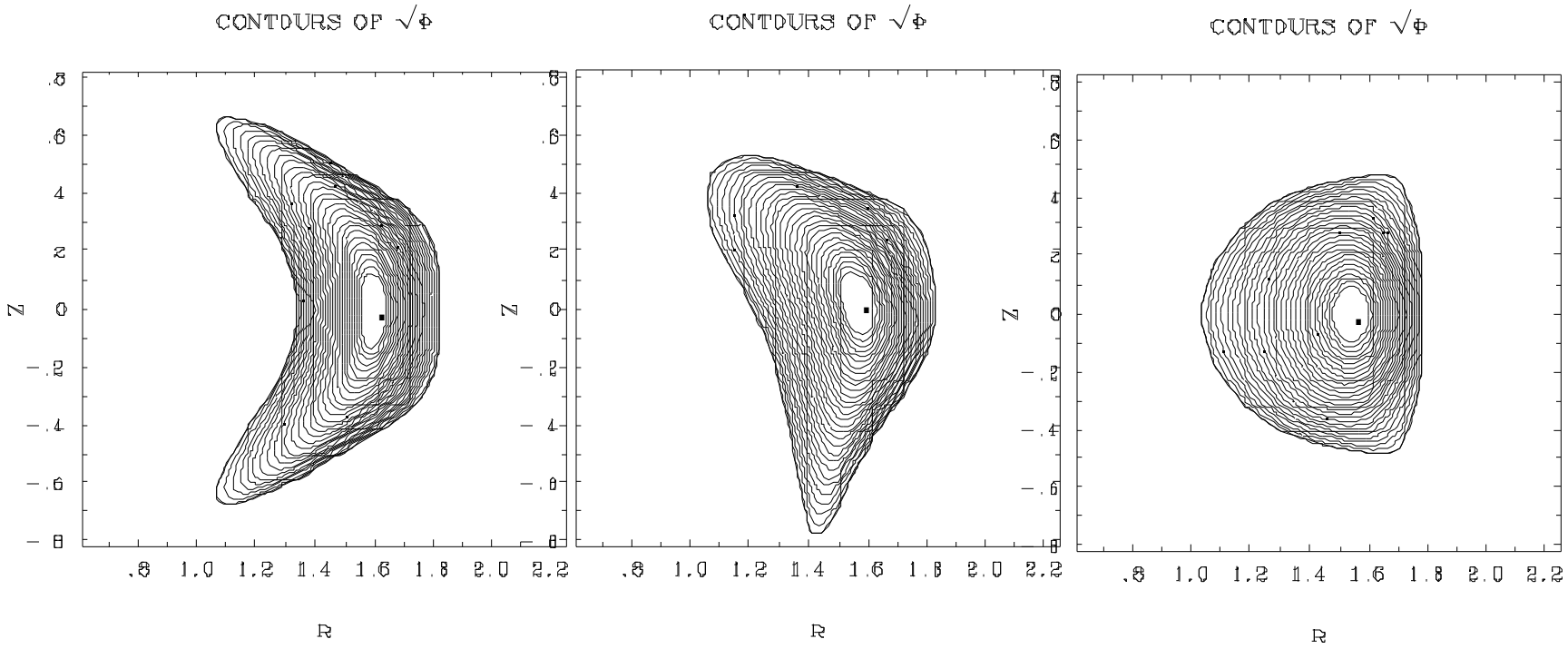


How good is good enough?

# Saddle Coils using 11 contour levels



# Poor reconstruction for Saddles with 11 contour levels



# QAS3_c10a Reconstruction Status

| Current Sheet | # Coils /period | Max Err,% | Mean Err,% | Coil Cur KA | Min Dist cm | j max MA/m | <M> | Reconstruction Status |
|---|---|---|---|---|---|---|---|---|
| Saddle | - | 2.12 | 0.15 | | | 3.77 | 2.296 | Very Good |
| Helical | - | 2.12 | 0.15 | | | 3.57 | 2.310 | Very Good |
| Modular | - | 2.11 | 0.15 | | | 2.86 | | Did not try ( expect very good ) |
| | | | | | | | | |
| Coils | | | | | | | | |
| Modular | 20 | 2.22 | 0.17 | 137.45 | 4.88 | 2.82 | 2.646 | Fair ( slightly Bumpy ) |
| Modular | 60 | 2.09 | 0.15 | 45.82 | 1.63 | 2.81 | 2.295 | Very Good |
| Helical | 14 | 2.16 | 0.19 | 58.91 | 1.67 | 3.53 | 4.107 | Poor ( Very Bumpy Surfaces ) |
| Helical | 30 | 2.34 | 0.23 | 27.49 | 0.86 | 3.20 | 2.276 | Very Good |
| Saddle | 30 | 2.25 | 0.32 | 31.09 | 0.90 | 3.45 | 2.460 | Good ( still visibly off ) |
| Saddle | 60 | 2.27 | 0.21 | 15.27 | 0.46 | 3.32 | 2.296 | Very Good |
| | | | | | | | | |
| Saddle | 10 | 6.01 | 1.38 | 93.27 | 2.63 | 3.55 | | Did not try ( expect worse than sad/heli) |
| Saddle/Helical | 11 | 4.41 | 0.79 | 84.80 | 2.51 | 3.38 | 2.776 | Fair-Poor ( moderately bumpy ) |
| Saddle | 12 | 5.03 | 1.06 | 77.73 | 2.17 | 3.58 | | Did not try ( expect worse than sad/heli) |
| | | | | | | ( =KA/cm2 at 10cm) | | |

Notes: The number of coils/period is actually the number of contours over the range.
For modular and helical, it represents the number of coils per period excluding
any additional saddles that may get generated. For Saddles it is the number of coils
between the max and min range of contours. Generally, the actual number of saddles is greater than this num

# Surface Offset Scan

- Investigated effect of varying surface offset from plasma to assess impact on errors, coil complexity and peak current density in current sheet solution (at constant m,n=10,10).
  - Error increase near linear with distance
  - Beyond 20 cm, peak current density increases exponentially
  - Coil also become increasingly more complex. Beyond 30cm coils extremely “ratty”
- Results were obtained with standard version of NESCOIL. Similar studies are underway using SVD and resonance suppression.

# Surface Offset Scan

## using Saddle Topology, Ipol=Itor=0. , with [m,n]=[10,10]

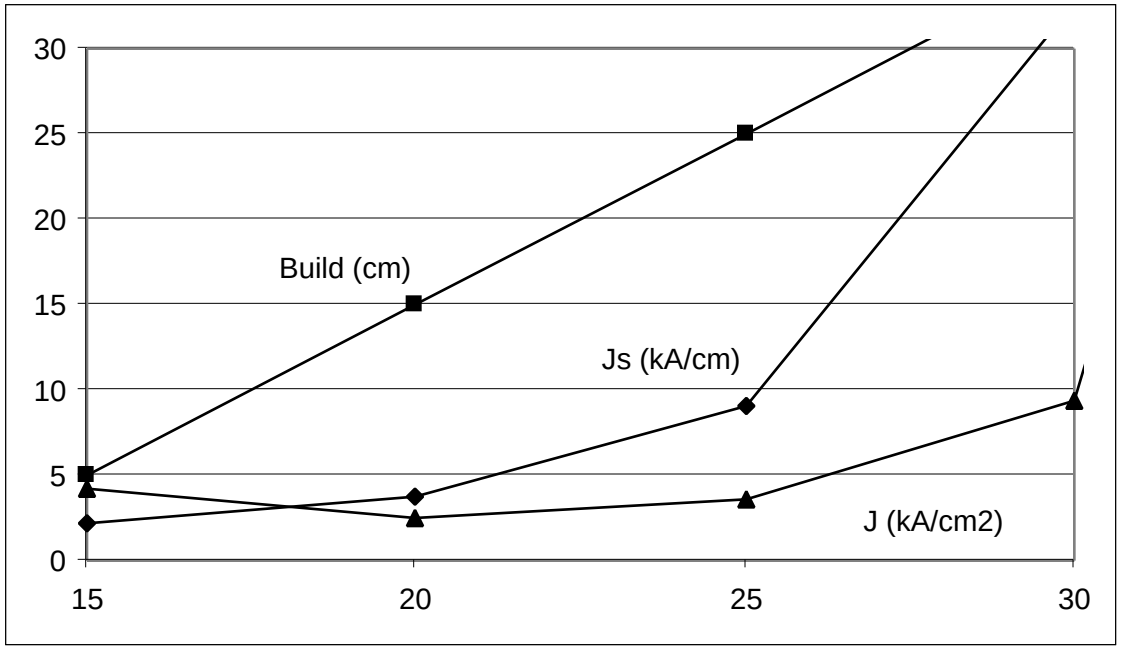
| Offset (cm) | Max Err (%) | Mean Err (%) | Offset (cm) | $J_{s,max}$ (MA/m) | Build[1] (cm) | $J_{ideal}$ (kA/cm2) | $J_{est}$[2] | Complexity |
|---|---|---|---|---|---|---|---|---|
| 5 | 6.32 | 0.64 | 5 | 1.57 | -15 | | | 2.77 |
| 10 | 2.17 | 0.12 | 10 | 2.34 | -5 | | | 2.75 |
| 15 | 2.09 | 0.11 | 15 | 2.14 | 5 | 4.29 | 13.00 | 2.89 |
| 20 | 2.12 | 0.15 | 20 | 3.77 | 15 | 2.51 | 7.61 | 3.22 |
| 25 | 2.13 | 0.2 | 25 | 9.13 | 25 | 3.65 | 11.06 | 4.14 |
| 30 | 2.58 | 0.25 | 30 | 32.71 | 35 | 9.35 | 28.32 | 5.77 |
| 40 | 4.4 | 0.36 | 40 | 766.97 | 55 | 139.45 | 422.57 | 5.42 |
| 50 | 5.84 | 0.46 | 50 | 16988.82 | 75 | 2265.18 | 6864.17 | 5.66 |

[1] Assumes a minimum separation of 12.5cm

[2] Assumes an overal copper fraction of 0.33

For Reference, the qas2_d9e plasma had a Js, max of 2.03 MA/m for saddles 2.25 MA/m for modulars. Target Jest (=Jcu) is 4.0 kA/cm2

# Surface Offset Scan




The available coil build decreases as the coil surface is moved closer to the Plasma, leading to a point (~20cm) where the coil current density is minimized.

# Coil Topology Scan

- Searched through alternate coil topologies looking for a win in terms of max/mean errors, current density or design simplicity ( amp-meters of conductor, coil curvatures, etc. )

- Investigated the effect of adding Toroidal Current to Saddle configuration ( Ipol=0 , Itor <>0 )

- Investigated varying helicity of coils:
  Itor/Ipol = +/- { 3, 2, 1, 1/2, 1/3 }

# Coil Topology Scan, sheet 1

| | Itor | Ipol | Itf | Ipf | Ncoils | DistMin cm | ErrMax % | ErrMean % | CurveMax 1/m | Energy MJ | AmpMeters MA-m | Current De MA/m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 0 | 54 | 2.79 | 6.00 | 1.39 | 191.1 | 1.34 | 22.29 | 3.77 |
| 2 | 0.5 | 0 | 1 | 0 | 16 | 3.46 | 11.00 | 3.36 | 76.5 | 2.92 | 25.84 | 4.29 |
| 3 | -0.5 | 0 | 1 | 0 | 14 | 5.68 | 9.70 | 1.75 | 900.9 | 2.77 | 23.15 | 3.33 |
| 4 | -0.25 | 0 | 1 | 0 | 36 | 3.49 | 6.47 | 1.38 | 562.7 | 1.62 | 20.58 | 3.55 |
| 5 | 0.25 | 0 | 1 | 0 | 38 | 2.59 | 4.48 | 1.23 | 1357.0 | 1.72 | 23.91 | 4.04 |
| 6 | 0.25 | -0.25 | 1.25 | 0 | 23 | 3.54 | 9.86 | 2.21 | 1395.0 | 2.83 | 27.28 | 4.48 |
| 7 | -0.25 | 0.25 | 0.75 | 0 | 23 | 5.02 | 6.15 | 1.61 | 101.1 | 1.73 | 22.60 | 3.11 |
| 8 | 0.25 | 0.25 | 0.75 | 0 | 11 | 4.31 | 7.17 | 1.54 | 391.8 | 1.89 | 24.27 | 3.60 |
| 9 | -0.25 | -0.25 | 1.25 | 0 | 11 | 3.82 | 7.53 | 1.69 | 428.7 | 2.55 | 27.12 | 3.99 |
| 10 | 0.16 | 0.16 | 0.84 | 0 | 11 | 3.16 | 3.10 | 0.81 | 9738.0 | 1.36 | 22.62 | 3.66 |
| 11 | -0.16 | 0.16 | 0.84 | 0 | 28 | 3.87 | 5.52 | 1.36 | 63.1 | 1.44 | 22.18 | 3.35 |
| 12 | -0.16 | 0.08 | 0.92 | 0 | 44 | 3.47 | 6.54 | 1.56 | 117.0 | 1.36 | 20.90 | 3.49 |
| 13 | 0.16 | 0.08 | 0.92 | 0 | 39 | 2.72 | 3.47 | 0.76 | 413.7 | 1.35 | 21.96 | 3.79 |

# Coil Topology Scan, sheet 2

| | Itor | Ipol | Itf | Ipf | Ncoils | DistMin cm | ErrMax % | ErrMean % | CurveMax 1/m | Energy MJ | AmpMeters MA-m | Current De MA/m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 0.25 | 0.125 | 0.875 | 0 | 28 | 2.45 | 5.29 | 0.94 | 1114.0 | 1.93 | 23.50 | 3.82 |
| 15 | -0.25 | 0.125 | 0.875 | 0 | 27 | 3.78 | 7.57 | 1.52 | 78.8 | 1.65 | 21.92 | 3.33 |
| 16 | 0.125 | 0.25 | 0.75 | 0 | 15 | 3.65 | 4.86 | 1.16 | 535.4 | 1.43 | 23.55 | 3.46 |
| 17 | 0.125 | -0.25 | 1.25 | 0 | 21 | 2.90 | 5.02 | 1.29 | 1755.0 | 2.24 | 26.24 | 4.34 |
| 18 | -0.125 | 0.25 | 0.75 | 0 | 15 | 4.09 | 6.44 | 1.21 | 140.3 | 1.51 | 23.03 | 3.22 |
| 19 | -0.125 | -0.25 | 1.25 | 0 | 15 | 3.16 | 5.40 | 1.22 | 1232.0 | 2.22 | 26.11 | 4.10 |
| 20 | 0.1 | 0.3 | 0.7 | 0 | 3 | 2.88 | 3.26 | 0.56 | 262.7 | 1.49 | 23.92 | 3.35 |
| 21 | 0.1 | -0.3 | 1.3 | 0 | | | | | | | | 4.43 |
| 22 | -0.1 | 0.3 | 0.7 | 0 | 14 | 4.68 | 6.21 | 1.50 | 522.4 | 1.52 | 22.48 | 3.16 |
| 23 | -0.1 | -0.3 | 1.3 | 0 | 8 | 3.52 | 6.70 | 1.57 | 1526.0 | 2.52 | 27.93 | 4.23 |
| 24 | 0.3 | 0.1 | 0.9 | 0 | 39 | 2.60 | 4.81 | 1.02 | 807.6 | 1.92 | 23.70 | 3.90 |
| 25 | 0.3 | -0.1 | 1.1 | 0 | 51 | 3.01 | 4.28 | 0.97 | 587.0 | 2.01 | 24.18 | 4.26 |
| 26 | -0.3 | 0.1 | 0.9 | 0 | 36 | 2.73 | 8.86 | 1.85 | 161.3 | 1.71 | 21.18 | 3.33 |
| 27 | -0.3 | -0.1 | 1.1 | 0 | 21 | 2.72 | 5.54 | 1.13 | 356.3 | 2.05 | 24.01 | 3.68 |

# Summary

- Codes and process seem to be working properly as demonstrated by successful reconstructions
- Low errors alone not sufficient to assure reconstruction
- Need to apply (displacement) resonance error to better understand poor reconstructions for realizable coils
- Coil filament to filament separation significantly impacts reconstructability
- Too large Coil to Plasma separation increases current density and coil complexity beyond feasiblity
- Need to further explore SVD benefits at larger offsets
- No big wins in current density from topology scan