

Edge Magnetic Field Line Structure In the Quasi-Axisymmetric Stellarator NCSX

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Introduction: NCSX

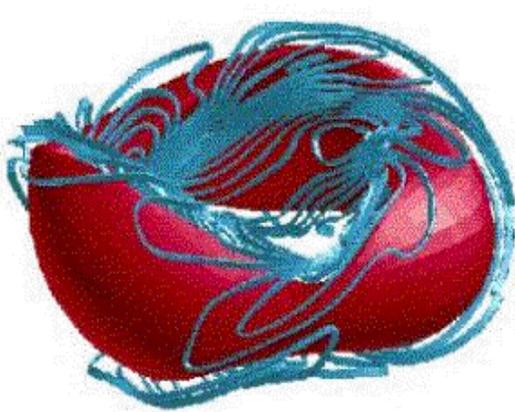
- The National Compact Stellarator Experiment (NCSX) is designed to have good quasi-axisymmetric (QAS) transport at parameters:
 - Major Radius $R \sim 1.75\text{m}$
 - Aspect Ratio $A = 4.4$
 - Number of Periods = 3
 - Range of $B=1\text{-}2\text{T}$
 - Flattop 0.7sec at 2T, 1.5sec at 1T
 - MHD stable to Volume Average $\langle\beta\rangle \sim 4\%$ without conducting walls or feedback.
- See S.P. Hirshman et al. Phys. Fluids 6(5) 1858 and adjacent posters HP1 26 to 35; talk UI1 1.

Introduction: QAS

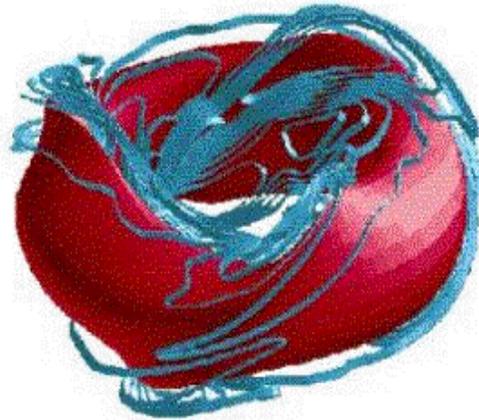
- Large transport losses of classical stellarators at reactor collisionalities overcome in QAS by tailoring the spectrum of $|B|$ to be nearly axisymmetric in Boozer flux coordinates.
- QAS has bootstrap currents comparable to a tokamak with same ι . (External transform fraction in NCSX: 60-81%.)
- QAS has an ι -profile which is modified by external coils to produce positive edge shear for kink and magnetic island suppression.

Introduction: Two Methods for Producing Vacuum Magnetics

Saddle Coils:



li383



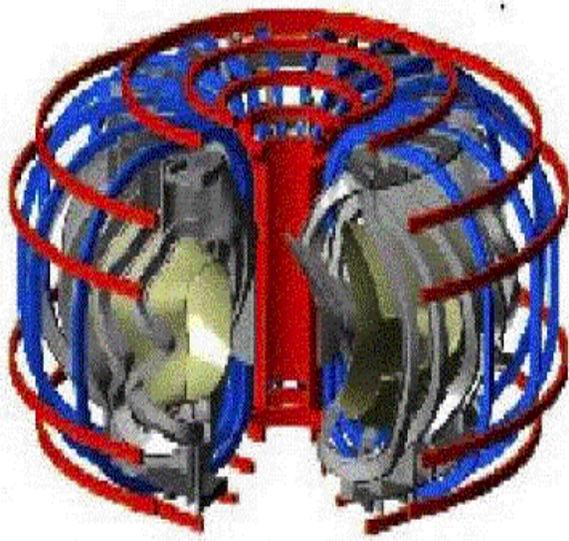
c82

Modular Coils:

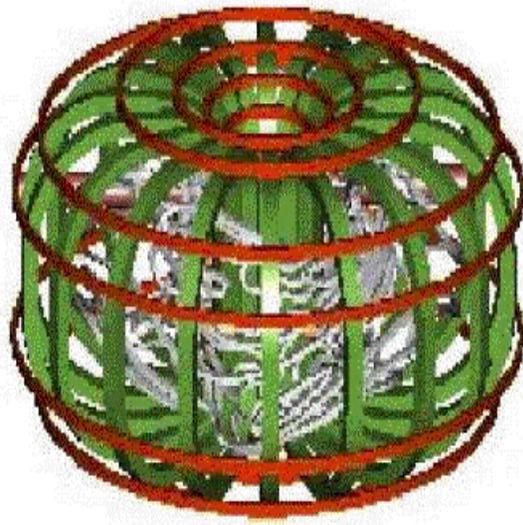


7 Coils / Period - 10 x 16-cm Xsec

Modular and Saddle Coil Design



Modular + Weak TF



Saddles + TF

Introduction: Reasons for Magnetic Field Structure Studies of These Configurations

- Stellarators lack the ordered magnetic field line structure found in the SOL of axisymmetric devices.
- Individual features of this boundary layer need to be considered for vacuum vessel and pfc design.
- Want small angles of incidence and large wetted areas to distribute power loads uniformly.
- Also want configurational flexibility, so these loads don't redistribute with changes in rotational transform, shear, beta, etc.

Numerical Method: VMEC

- Newly revised version of the VMEC code (VMEC2000) used to compute the free boundary equilibrium. See also poster HP1 30 and talk UI1 1.
- Earlier VMEC version references:
 - S.P Hirshman, W.I. Van Rij, P.Merkel, Comput. Phys. Comm. 43 (1986) 143.
 - S.P Hirshman, D.K. Lee, Comput. Phys. Commun. 39 (1986) 161.
- VMEC code considers only nested flux surfaces and therefore no islands can be studied inside LCMS. PIES and HINT code are able to treat islands (but not outside LCMS). See also posters HP1 27 and HP1 28 and invited talk UI1 1.

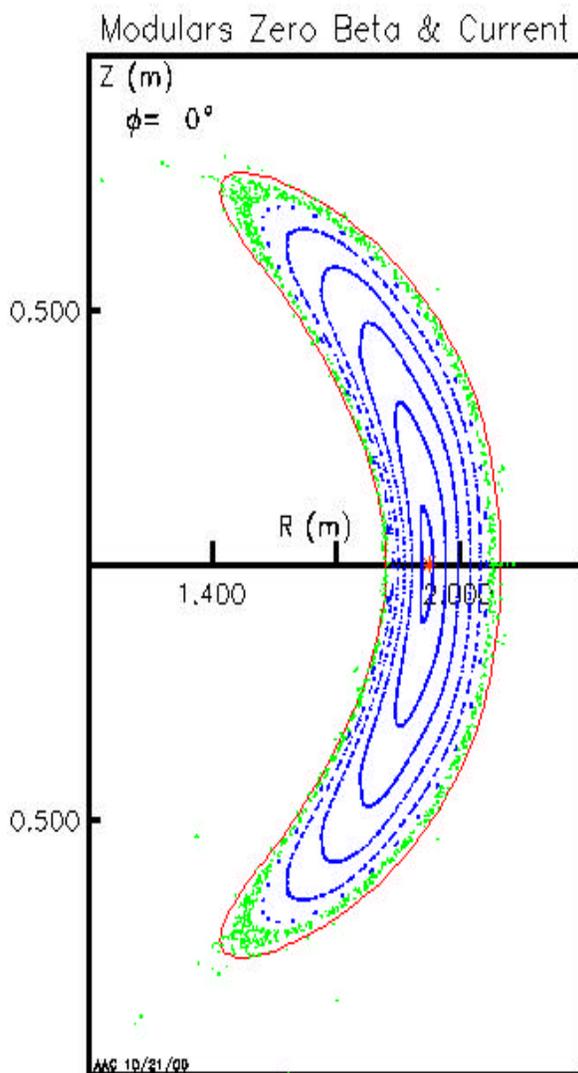
Numerical Method: MFBE

- Magnetic Fields of Finite Beta Equilibria (MFBE) is a new magnetic topology code developed by E.Strumberger, (Nucl. Fus. 1997.). Prior calculations used vacuum magnetic fields outside LCMS.
- We are using a newer version of MFBE (extended with respect to Nucl. Fus. 1997) to treat equilibria with toroidal current via the ‘virtual casing principle’ of V.D. Shafranov, L.E. Zakharov Nucl. Fus. 12 (1972) 599.
- Calculates all magnetic fields of finite-beta free boundary equilibria with plasma currents on a grid whose nodes may be arbitrarily close to the plasma boundary.

Numerical Method: Field Line Tracing and PHIEDGE

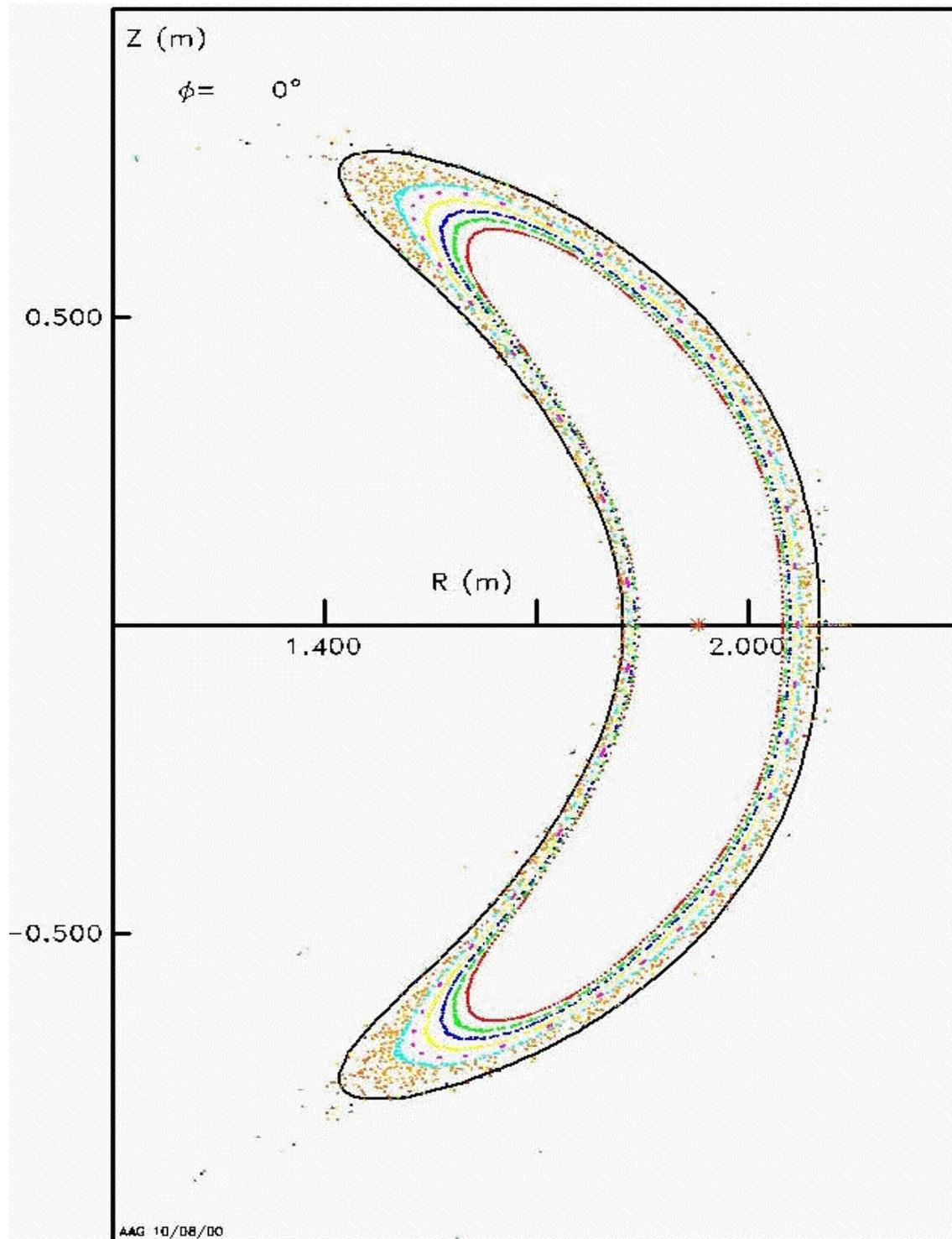
- Gourdon code is used for field line tracing.
- Iterative Determination of the Toroidal Flux (PHIEDGE is a free parameter of the VMEC code.)
 - Choose a small toroidal flux
 - Free boundary equilibrium
 - Magnetic Field line Tracing
 - Closed magnetic surfaces outside the plasma boundary
 - increase toroidal flux and repetition of numerical calculations until last closed magnetic surface obtained by field line tracing coincides with the plasma boundary of the free-boundary equilibrium.

Poincare Plot - Vacuum Field Modular Coils

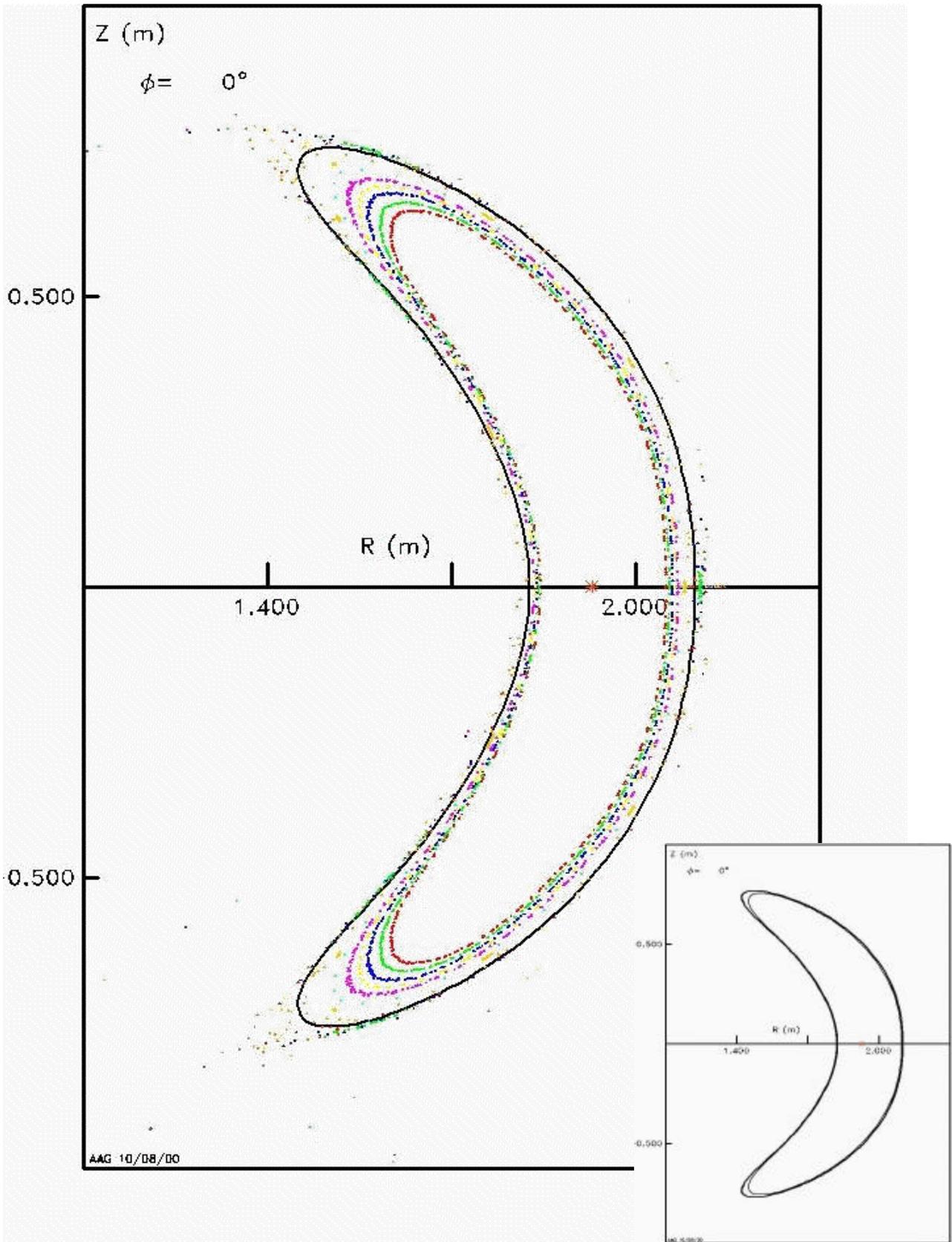


- Blue-Magnetic field lines which form closed surfaces.
- Green- Ergodic field lines
- Red- Plasma boundary from VMEC
- Toroidal Flux (PHIEDGE) = 0.740

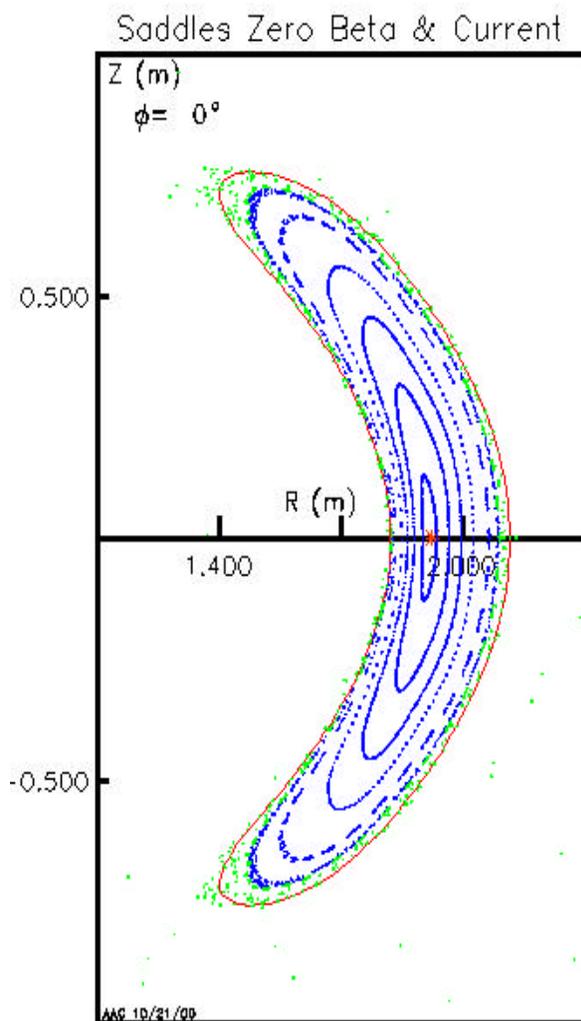
Modular zero current, zero beta: $\iota = 0.533$
 $= 15/28 \implies 28$ islands (pink field line has
 $\iota = 0.533273$) Toroidal Flux = 0.740



Modular Zero Current, Zero Beta at Lower Toroidal Flux=0.700: Further Reduction Needed

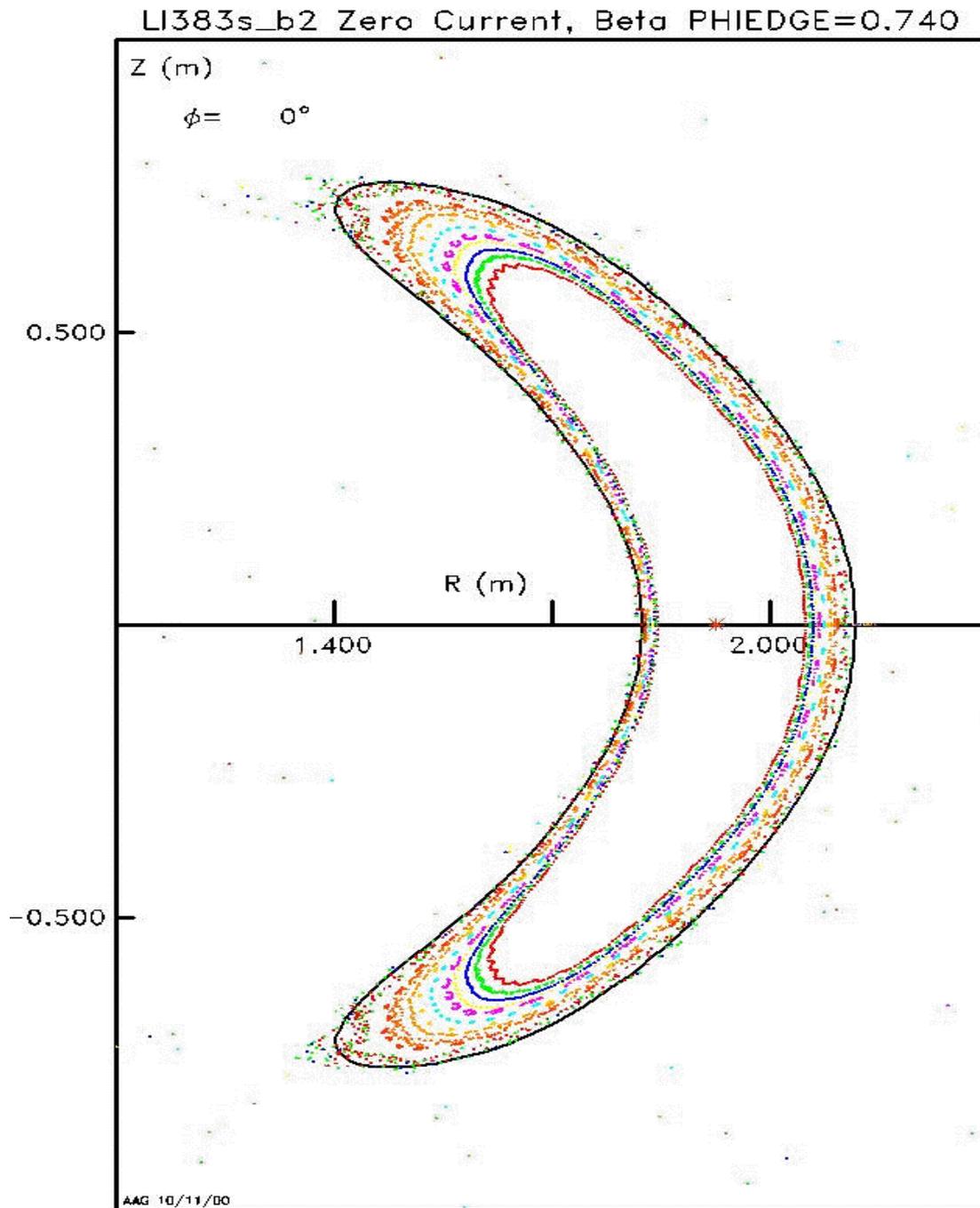


Poincare Plot - Vacuum Field Saddle Coils

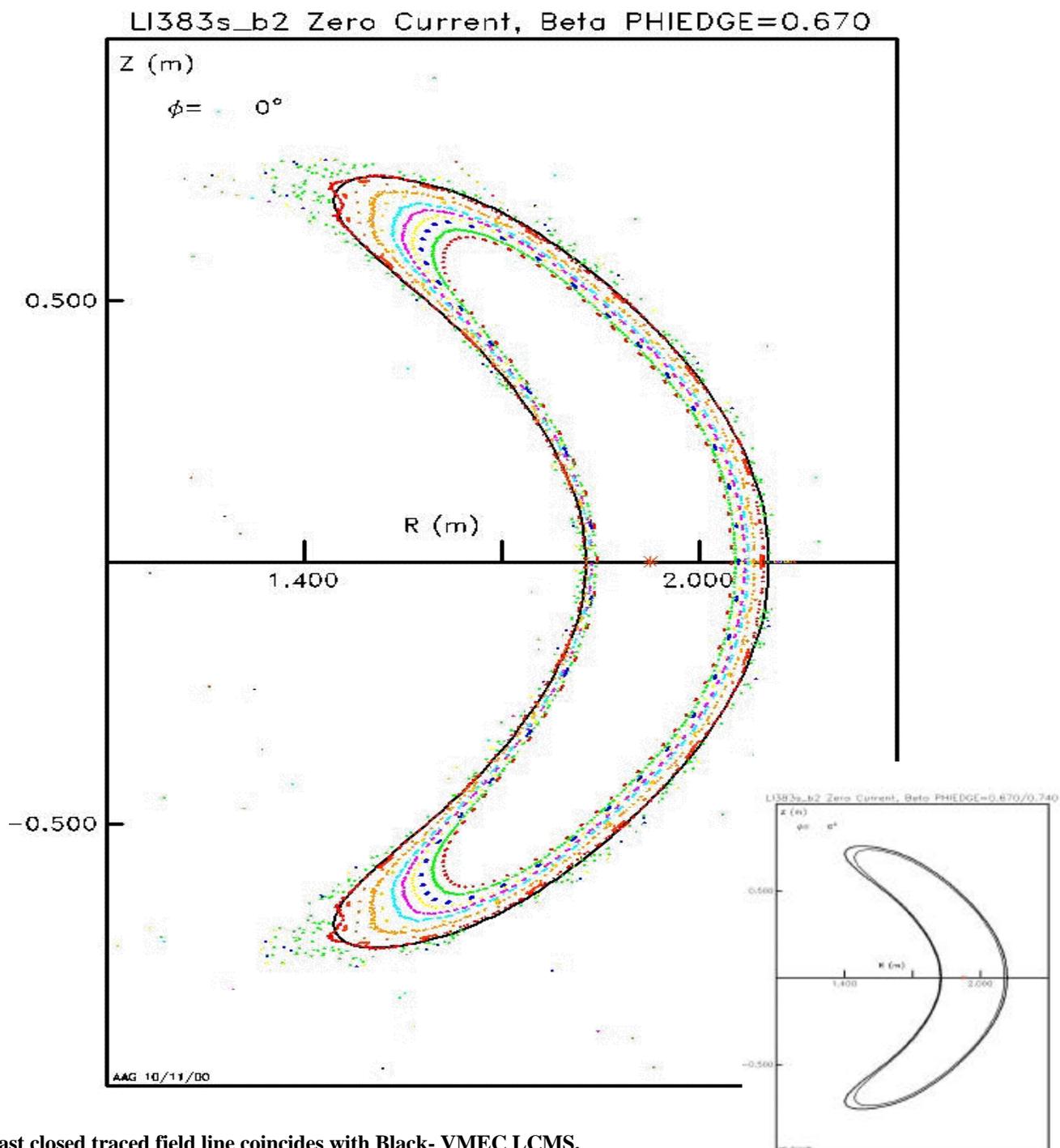


- Blue- Magnetic field lines which form closed surfaces.
- Green- Ergodic field lines
- Red- Plasma boundary from VMEC
- Toroidal Flux (PHIEDGE) = 0.740

Saddle coils, zero current, zero beta $0.517 = 15/29 \implies 29$ islands (red field line has iota 0.517503) Toroidal Flux = 0.740

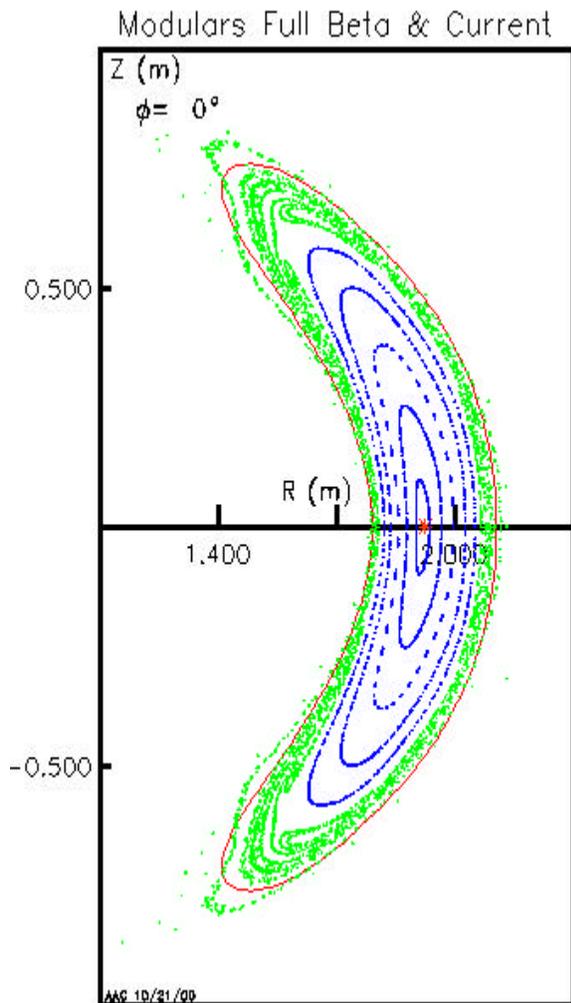


BEST RESULT: Saddle Coils Zero Beta, Zero
Current at Lower Toroidal Flux = 0.670
LCMS from field line tracing coincides with VMEC
plasma boundary



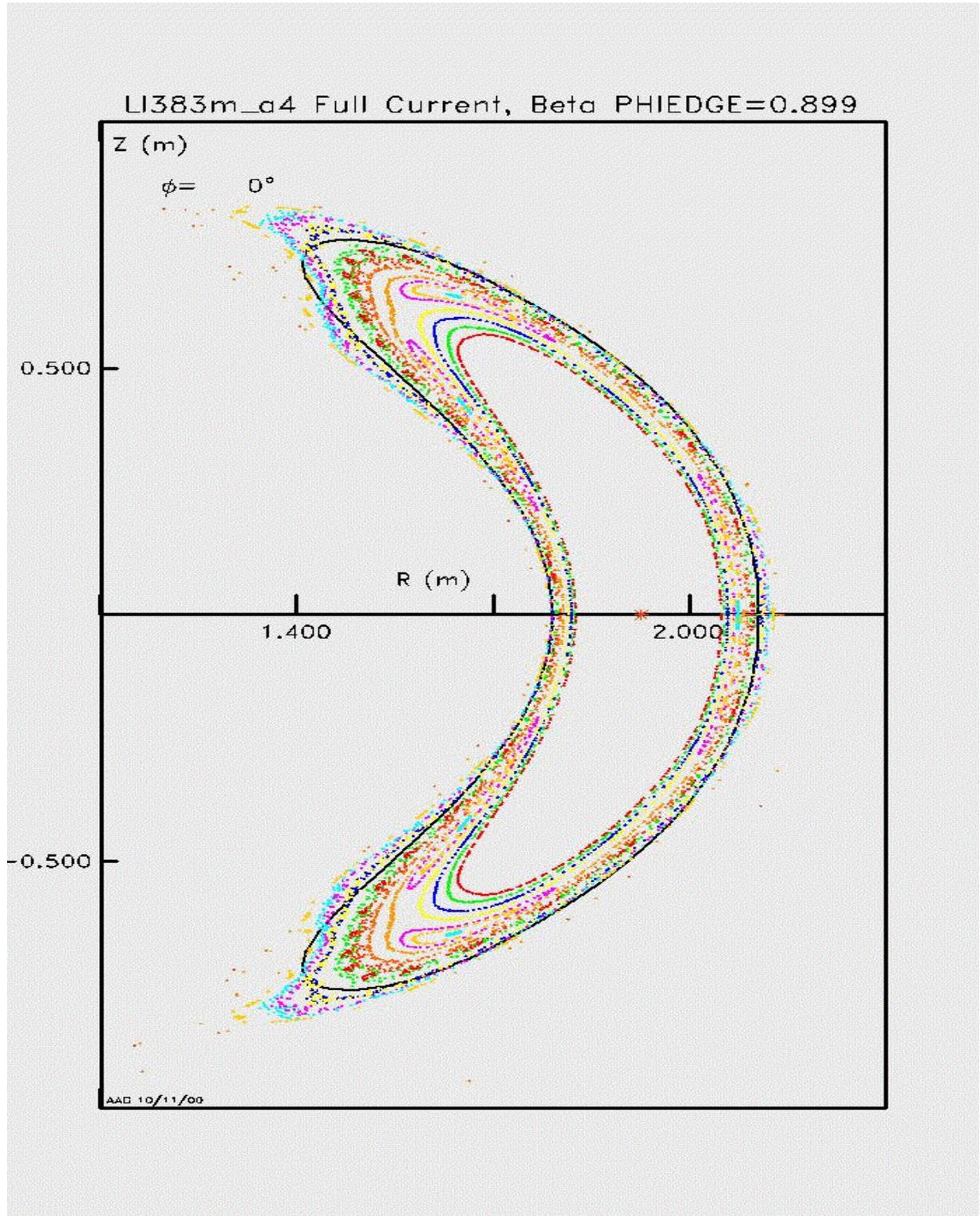
Red- Last closed traced field line coincides with Black- VMEC LCMS.

Poincare Plot - Full Beta Magnetic Field Modular Coils, Toroidal Flux=0.899



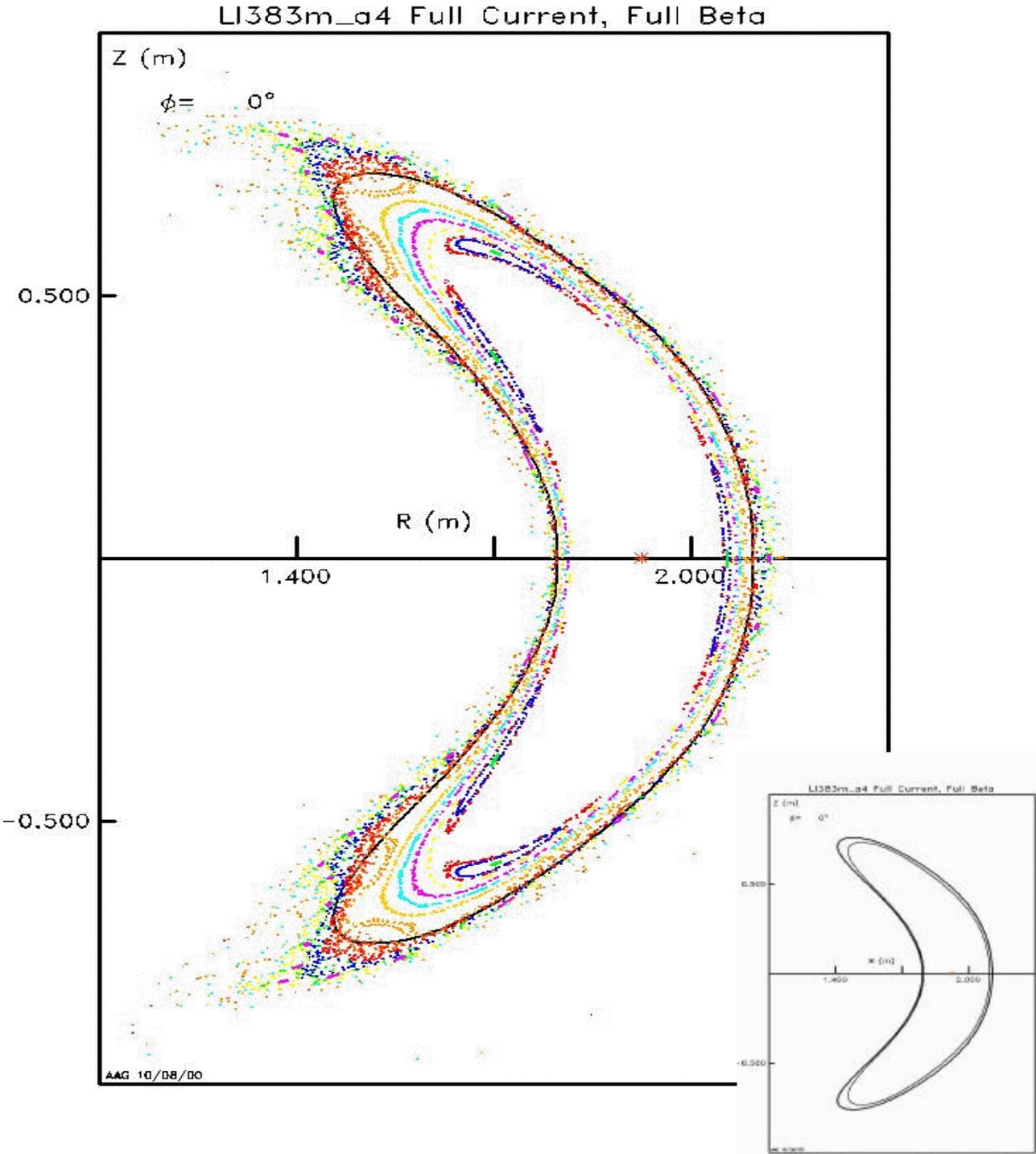
- Complex island structure inside the plasma boundary, in full beta, full plasma current equilibria.
- VMEC cannot handle islands. MFBE is hinting that islands may exist inside LCMS. Only PIES can find true island size inside LCMS, not MFBE
- MFBE LCMS shows complex shape.

Modular Full Beta, Full Current Iota =0.636
=21/33 ==> 33 islands (red field line has iota
=0.636429 yellow field line has iota = 0.633815)
Toroidal Flux=0.899

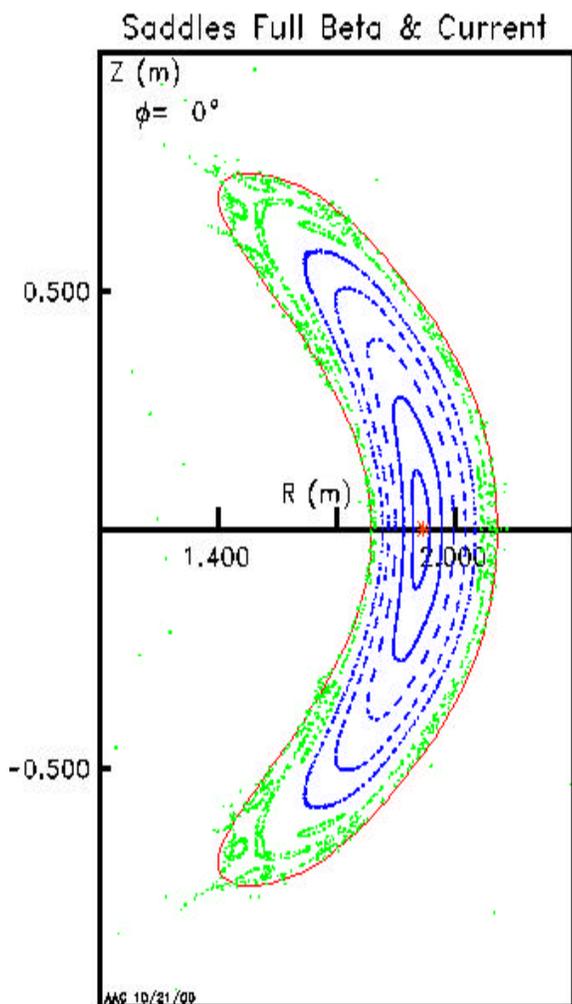


Modular Coils Full Beta Full Current at Lower Toroidal Flux = 0.800

No Improvement to Complex Island and Ergodic Structures Near LCMS

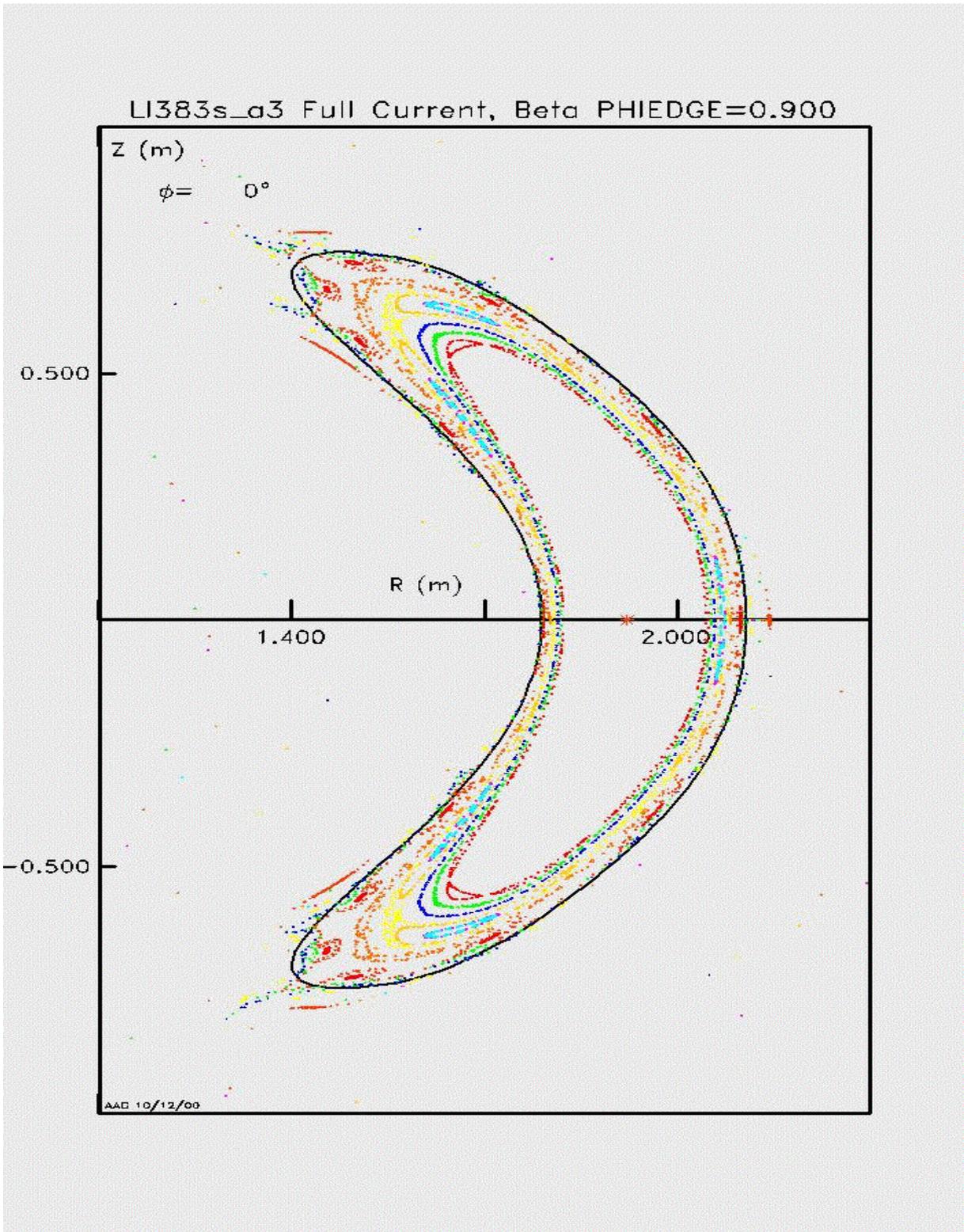


Poincare Plot - Full Beta Magnetic Field Saddle Coil, Toroidal Flux=0.9

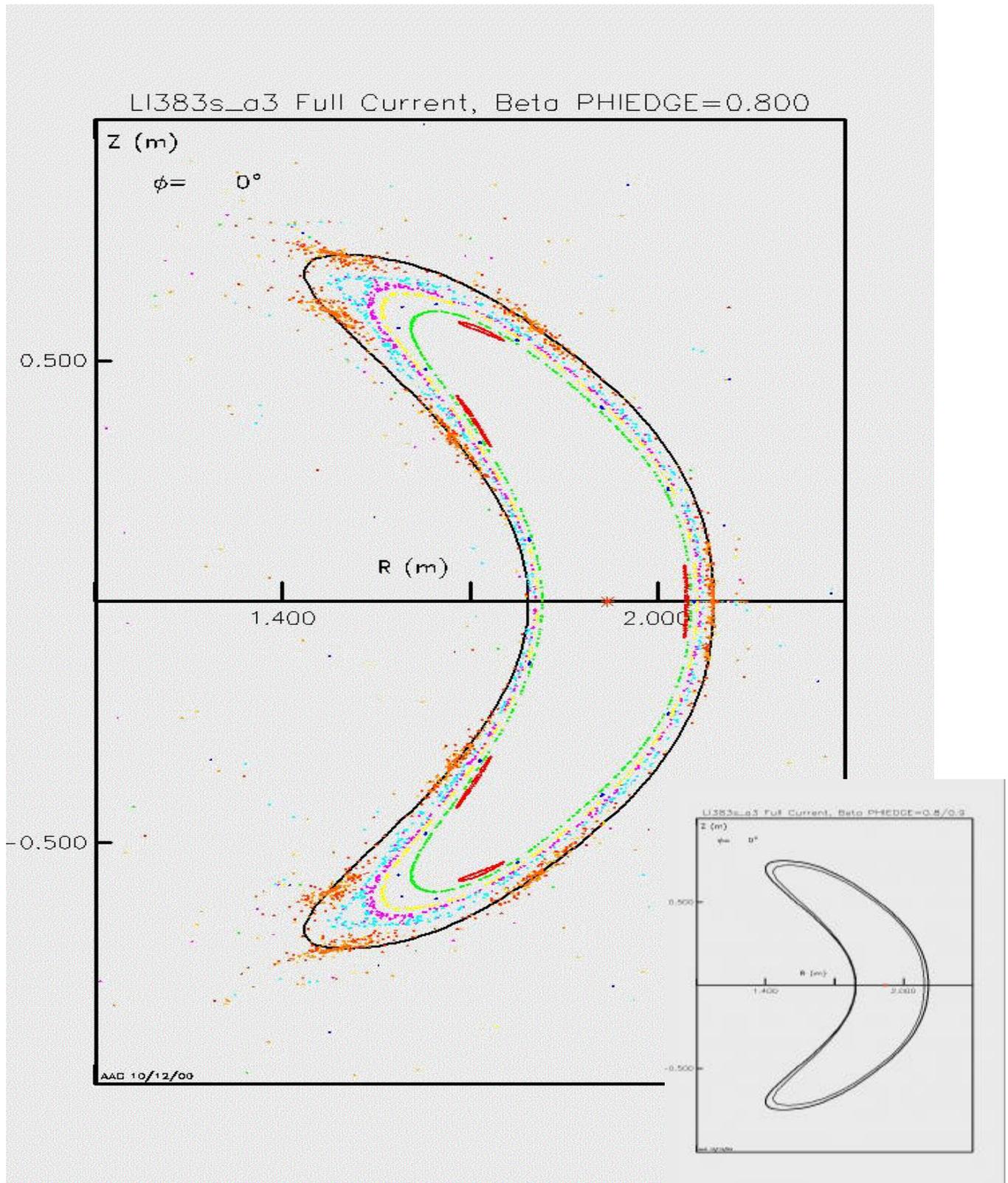


- Complex island structure inside the plasma boundary, in full beta, full plasma current equilibria.
- VMEC cannot handle islands. MFBE can only hint that islands may exist inside LCMS, but can't give true size. MFBE can fully calculate any islands widths outside.
- MFBE traced LCMS shows more complex shape than modulars.

Saddle Coils: Full Beta, Full Current
 $\iota = 0.642 = 9/14 \implies 14$ islands
(red-orange field line has $\iota = 0.641545$)
Toroidal Flux = 0.900

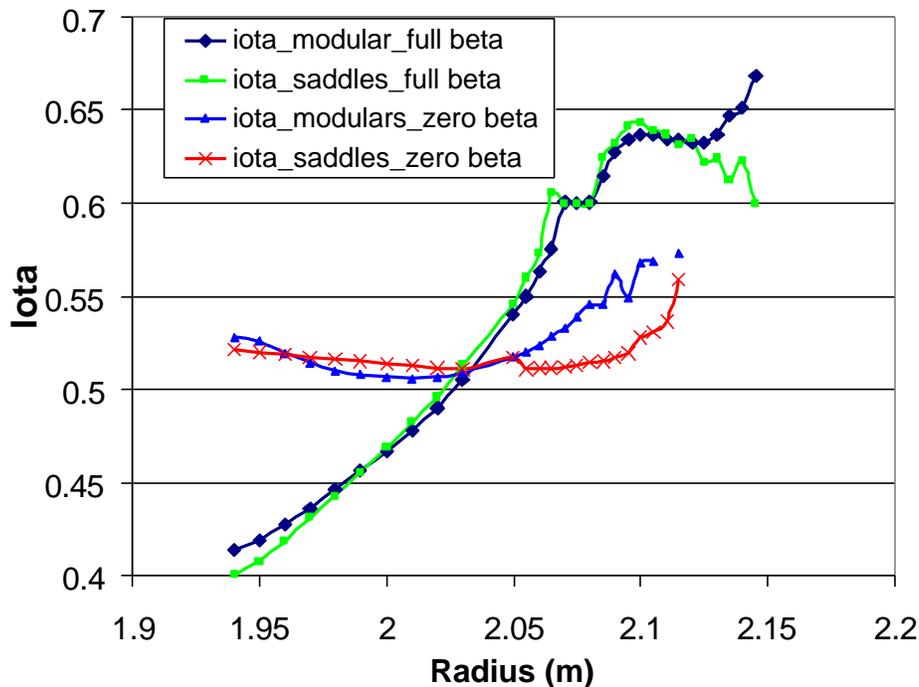


Saddle Coils Full Beta, Full Current at Lower Toroidal Flux = 0.800 No Improvement to Complex Structure Near LCMS



Comparison of Vacuum and Full Beta Fields: Iota Calculated from Field Line Tracing

Rotational Transform vs. R



- In the full beta equilibria there are 5 islands inside and 5 island remnants outside the plasma boundary. Iota increases from the magnetic axis to the plasma boundary and then decreases again. Important low order rational value of $\text{iota} = 0.6 = 3/5 \Rightarrow 5$ islands.
- Large islands in the edge region which could be used for an island divertor have not been found yet. Distortions to the closed surfaces due to island remnants are observed in these plots. No islands in the vacuum cases.
- The differences of iota values are significant enough to account for differences in the observed field line tracing patterns. Iota decreases and flattens in the vacuum case, so as to eliminate low order rational values.

Conclusions

- The magnetic topology of the quasi-axisymmetric stellarator looks much more complicated than that of W7-X, which has no plasma current.
- The vacuum fields have a relatively simple topology. The zero current, zero beta equilibria avoid islands by avoiding the low order rational values for iota.
- In the full beta, full current equilibria there are hints of five islands inside the plasma boundary and five islands outside the plasma boundary. The low order rational iota of $0.6=3/5 \Rightarrow 5$ islands appears to govern these islands. Also seen in the field line tracings are higher order rational iota islands, but these do not distort the surface topology as much.
- Comparing the patterns of the traced field lines and the shape of the plasma boundary suggests that the VMEC solution at full beta and full current does not reproduce the real plasma boundary.

Reasons include:

- The extended five islands inside the plasma boundary. VMEC cannot take into account these islands. It would be a good check of the MFBE results if these were compared with PIES code.
- If the plasma boundary has a complicated structure, the mode numbers and the number of grid points used in VMEC ($\mu=9$, $m\nu=5$, $n\nu=24$, $n\nu=16$) are not enough to reproduce this boundary. More computations are needed to check numerical accuracy here.
- The toroidal flux used by VMEC may be too large. Iterative determination of this toroidal flux improved agreement in the vacuum field equilibria, but did not help improve agreement in the full beta, full current cases.