MAGNETIC FIELD ERRORS: RECONCILING MEASUREMENT, MODELING AND EMPIRICAL CORRECTIONS ON DIII–D

by

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GENERAL ATOMICS

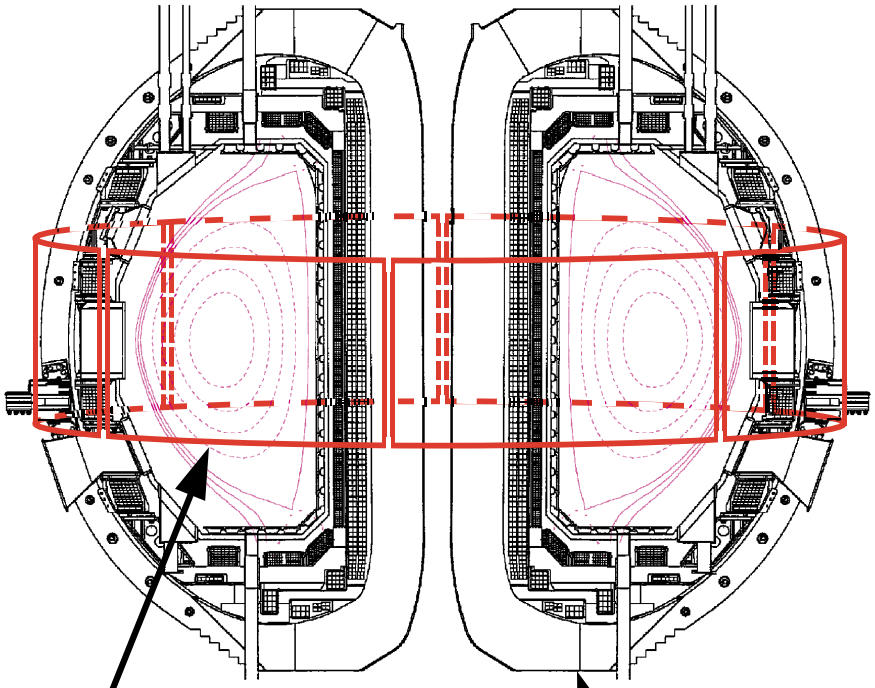
Introduction

- Non-axisymmetric magnetic errors can have deleterious effects on tokamak plasmas.
- Interaction between magnetic field errors and plasmas must be understood to rationally design effective error correction systems for future magnetically confined fusion experiments.
- A correction coil set (C-coil) compensates errors in DIII–D since 1994.
  - Uses *empirical* algorithms.
- Magnetic errors in DIII–D were carefully remeasured in 2001 Nov.

$\Longrightarrow$ The empirically optimized correction fields *add to*, (not cancel) the measured errors.

- We attempt to understand this puzzling error–plasma interaction through numerical magnetic line tracing.

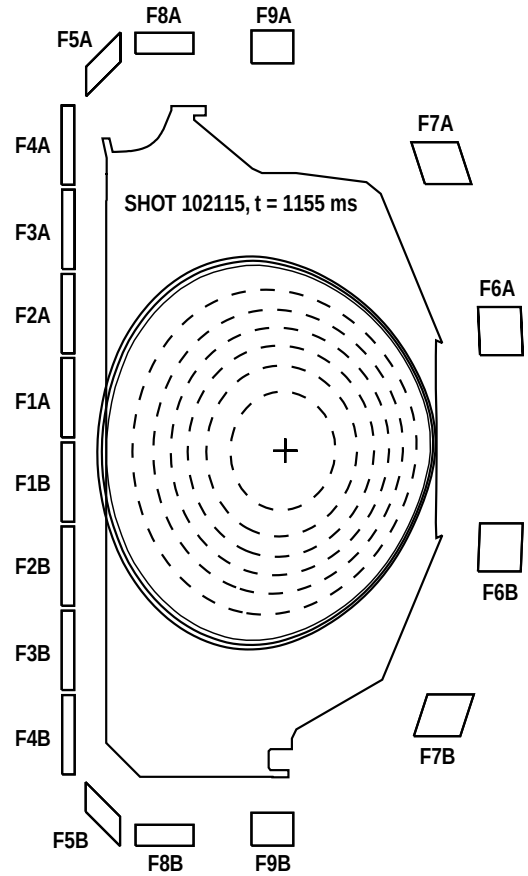
Magnet Coils of Main Interest for Error Analysis
DIII–D in Year 2001-02



C–Coil Set
(Correction Coils)

B–Coil
(Toroidal Field Coil)

F–Coils
(Poloidal Field Coils)



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Some DIII–D Magnetic Error Background

- 1990: Measured F–coil errors (LaHaye & Scoville).
- 1994: Installed Correction coil (C–coil).
- 1994–97: Developed empirical algorithms (with theoretical guidance) to minimize low-density mode locking (LaHaye & Scoville).
  - Empirical correction did *not* match 1990 measured errors (LaHaye).
- 2000–1: Error field amplification by plasma increases sensitivity to errors. New empirical C–coil algorithms to minimize plasma rotation braking in Resistive Wall Mode studies are not greatly different. (Garofalo).
  - All empirical algorithms contain strong dependence on B_T.
  - Imply ≈ 7 gauss m,n = 2,1 B-coil component at q = 2 surface.
  - Is there an unknown error from toroidal field coil?
- 2001 Sept: Decided to do through search for and measurement of magnetic errors in DIII–D.

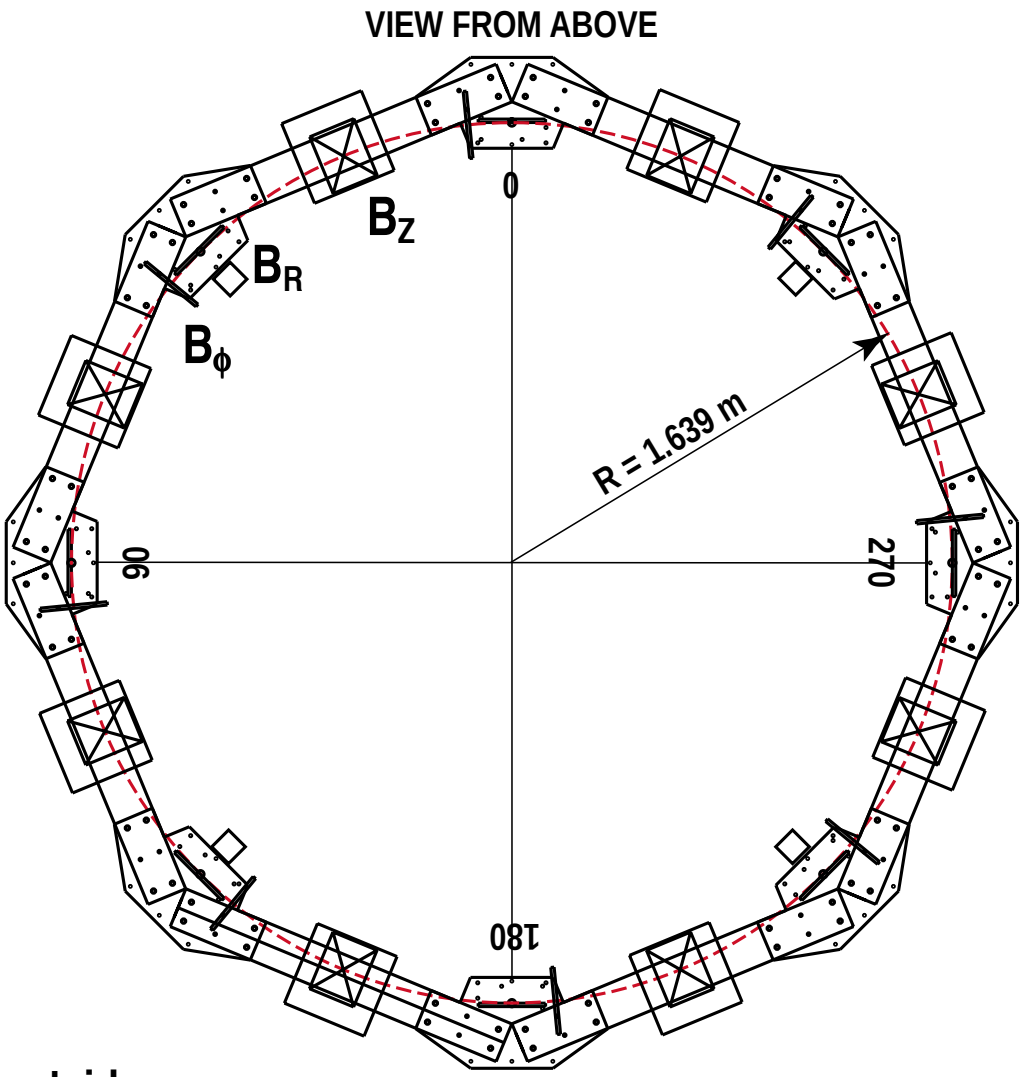
ERROR MEASUREMENTS

In-Vessel Probe Array for Error Measurements was Rebuilt

- Octagonal frame disassembles to enter DIII–D (LaHaye).
- Frame slides vertically along four legs.
- Planar spiral inductive probes on printed circuit boards (Jackson).
- 3 components (B_R, B_ϕ, B_Z), each at 8 toroidal locations.
- Reassembly inside DIII–D

  Must maintain planarity, circularity and centering of the *array*.

  Must maintain orientation of the *probes*.



- Other probes distributed outside and in central bore.

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In-Vessel Array, Illustrating Magnetic Pickups and Hoist

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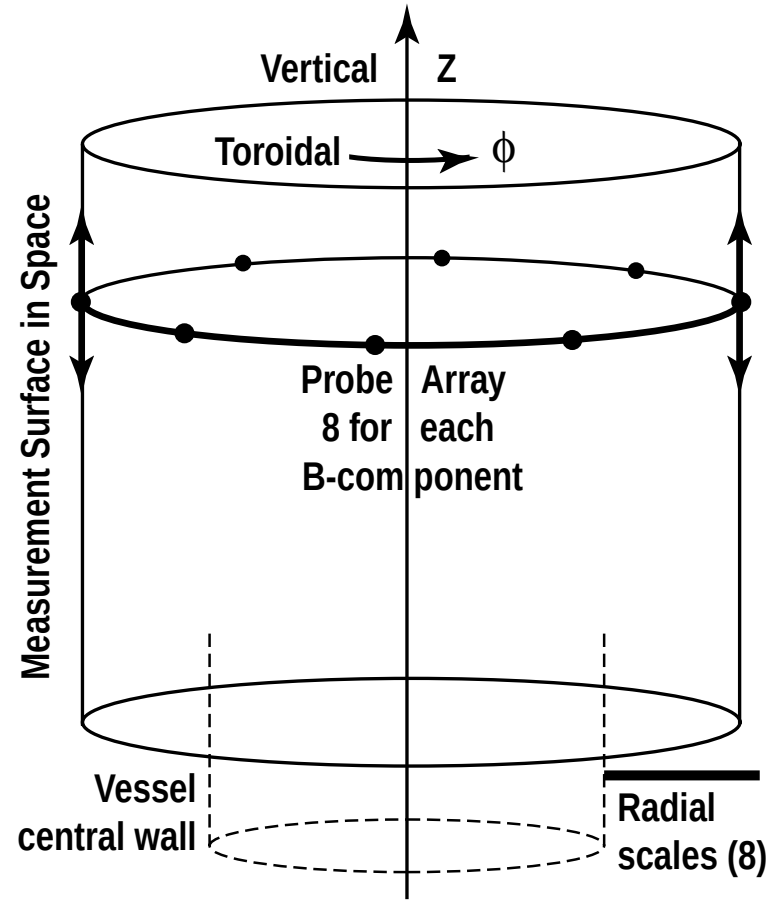
Measurement Coordinate System Is Chosen for Ability to Reproduce It

- Make all in-vessel measurements in one reproducible vertical cylindrical coordinate system (right handed).



After every change of array position:

- Make array level and flat to gravity
- Center probe circle on vessel inner wall
  - 8 radial scales bolted to vessel
  - 8 plumb bobs hang from probe array
  - ≈ ±0.5 mm centering reproducibility
- Check array circularity
- Level B_Z probes. Plumb B_R and B_ϕ, probes.
  - ≈ ±0.0005 rad ≈ ±0.03° reproducibility

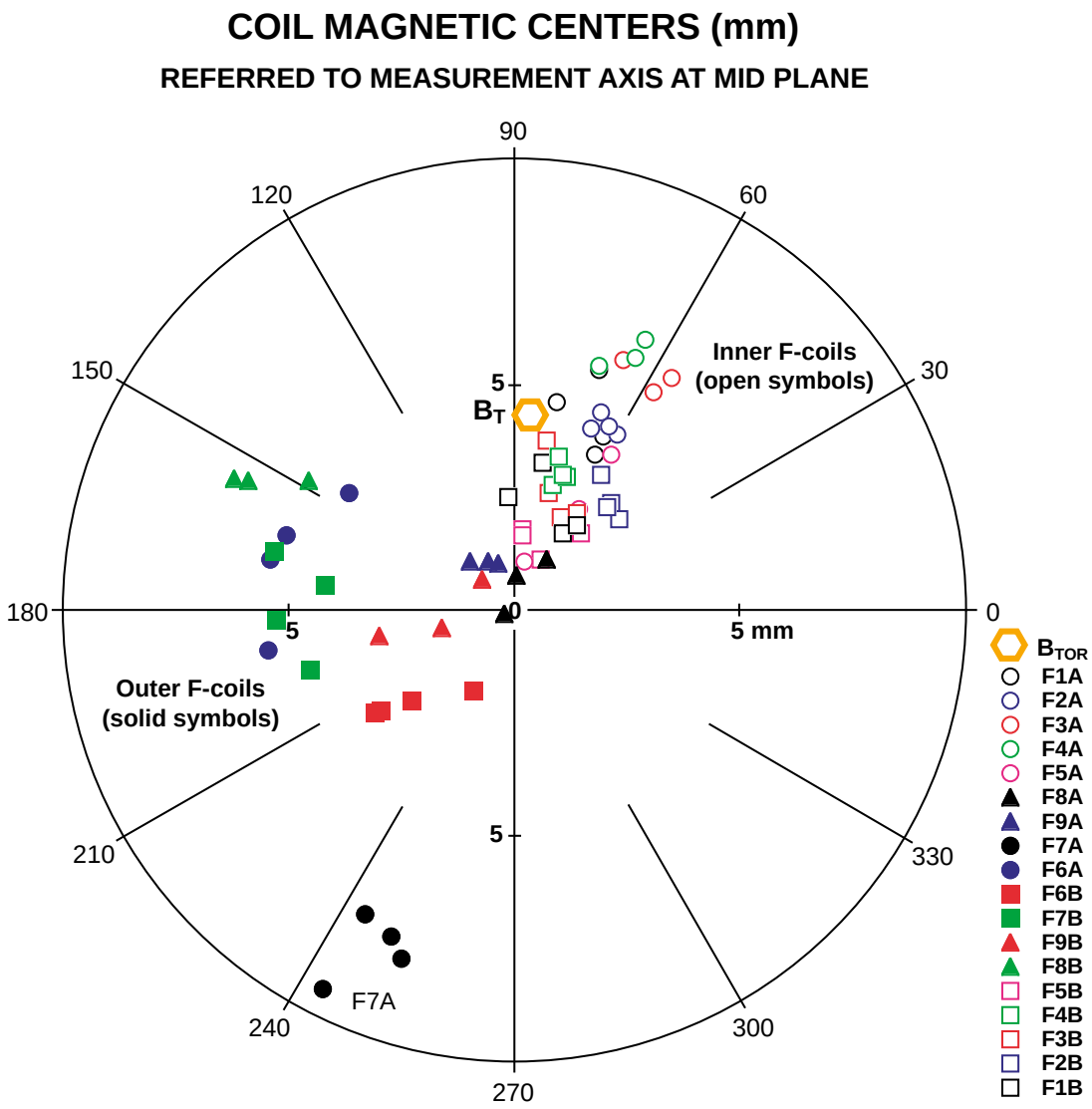
Also:

- Rotated array 65° once, to separate probe errors from true δB, also to synthesize 16 element array.

RESULTS

MAIN RESULT: The Largest Magnetic Errors in DIII–D Are Shifts of F–Coil Centers with Respect to the Toroidal Magnetic Field

- Other errors are much smaller:
  - Centerpost nonuniformities
  - Old "N = 1 coil" frame
  - B–coil feeds
  - Iron diagnostic shields
- NO LARGE NEW ERROR SOURCE WAS FOUND.
- Newly measured shifts are mostly smaller than from 1990 data.
  - i.e., DIII–D has *smaller* magnetic errors than thought previously.



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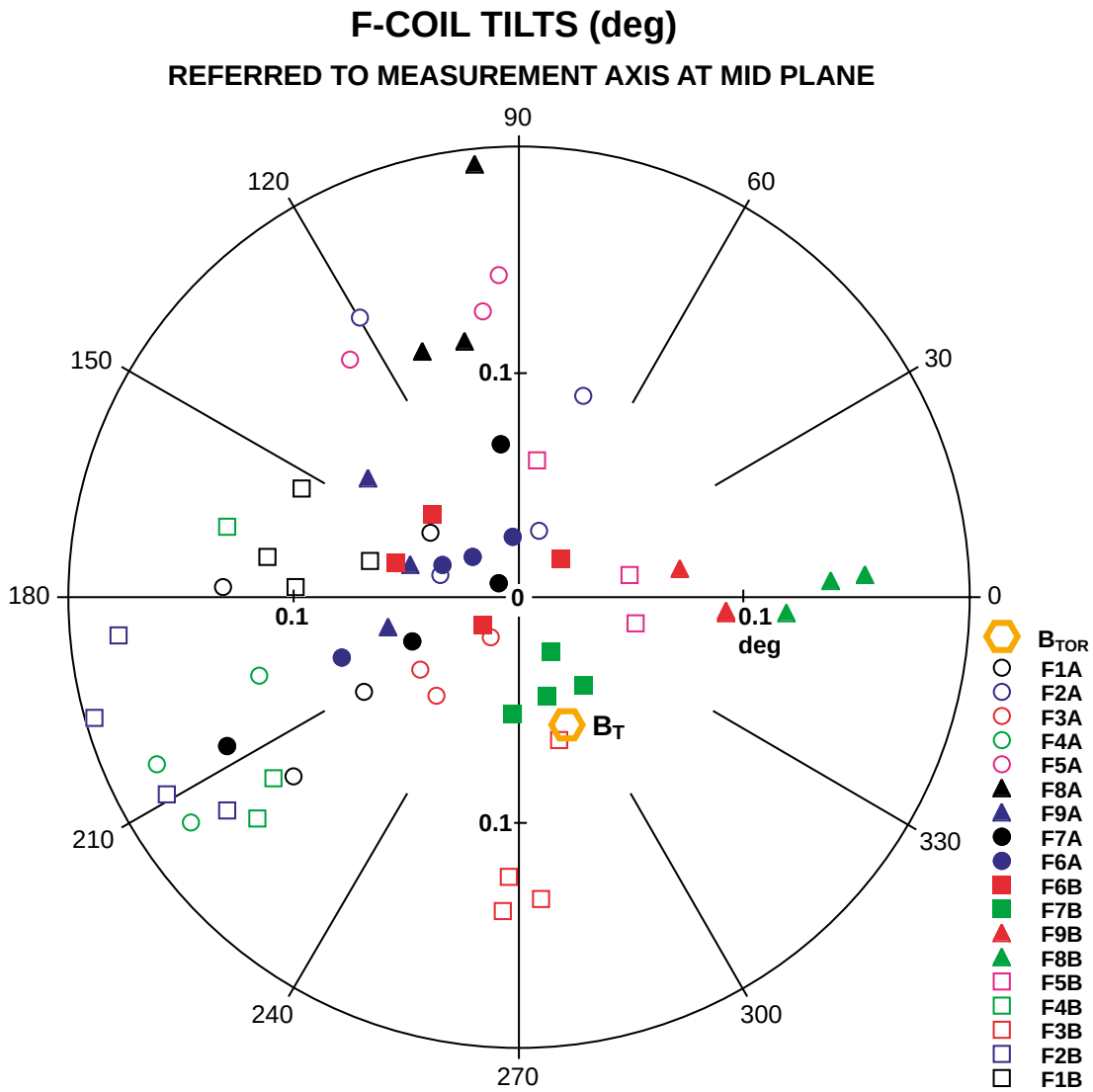
RESULTS: F–Coils Are Also Tilted

- Newly measured tilts are less than inferred from 1990 measurements.
  - The old N = 1 coil ferromagnetic frame tilted the fields of the uppermost F-coils in 1990.

Points on figure show tilt of coil plane, upward at the toroidal angle shown.



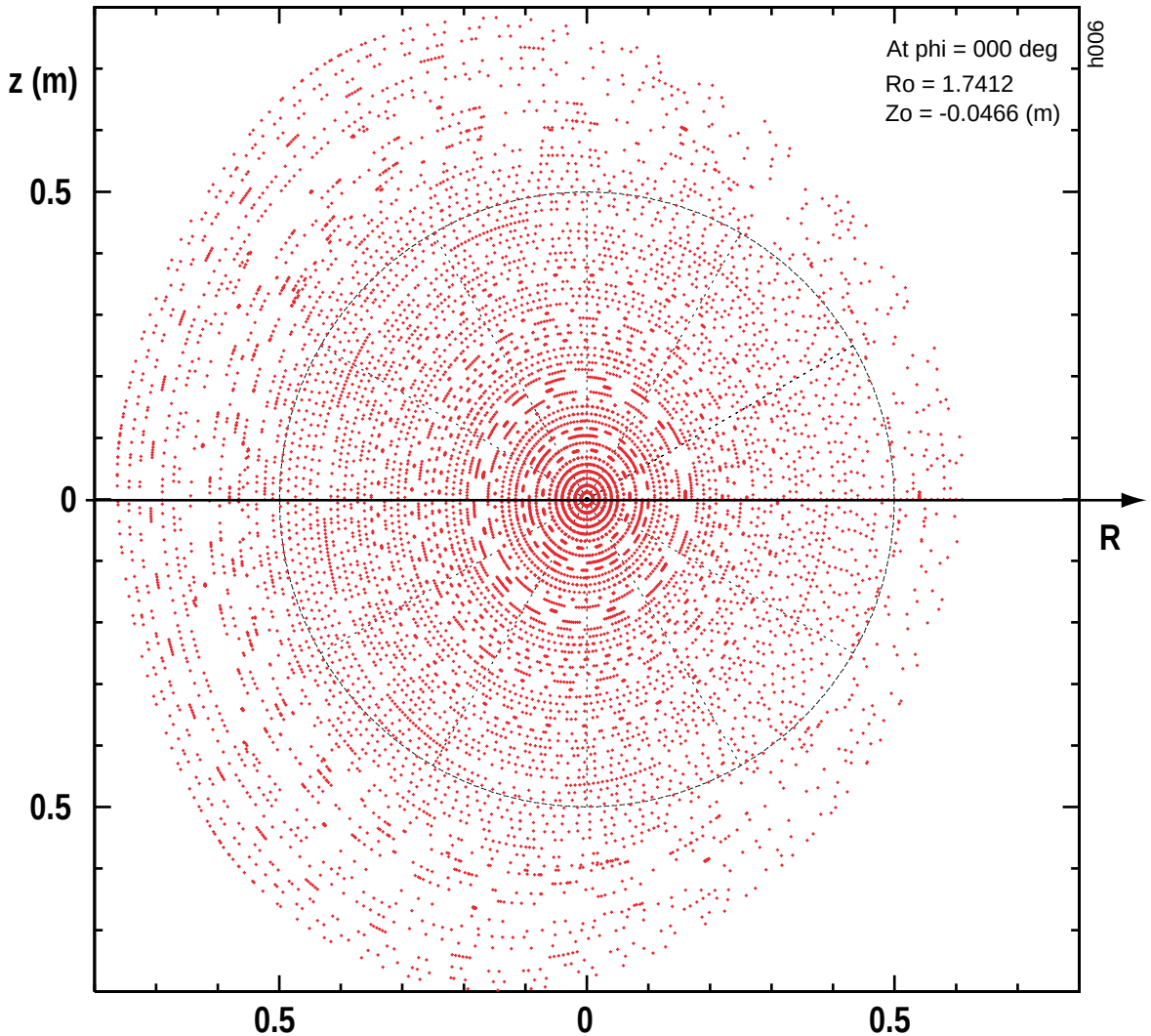
ANALYSIS

Magnetic Line Tracing Code is the Main Tool Used to Date

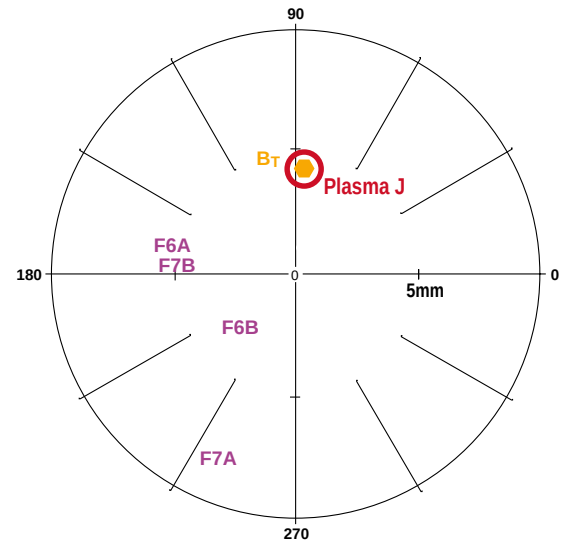
- DIII–D version of the TRIP3D line tracing code (T.E. Evans)
- Axisymmetric equilibrium B is calculated from an EFIT "g-file"
  - Can independently shift and tilt toroidal and poloidal fields of the equilibrium (*rigid* shifts and tilts)
  - Can change B_{Tor} magnitude (usually to change q)
- Shifted F–coils
  - Code subtracts the concentric F–coil contribution to B_{Pol} from the equilibrium, so only the error part remains
  - F–coil tilt is not yet implemented in TRIP3D
- C–coil fields
- But: *NO PLASMA RESPONSE* to errors

Magnetic Line Tracing Model Results: Off-Center F–Coils Alone Make Modest (≈ 2 cm-wide) 2,1 Islands, if Plasma Current Follows B_T

Plasma Current Centered on B_T. No C-Coil Current.



Coil-Center Locations on Measurement Coordinates



Measured Coil Centers

Case: Plasma Current centered on B_T.

(No C-Coil Current)

(No tilts)

Equilibrium fields from shot 102115

Limited, nearly circular ($\kappa \approx 1.15$) for simplicity.

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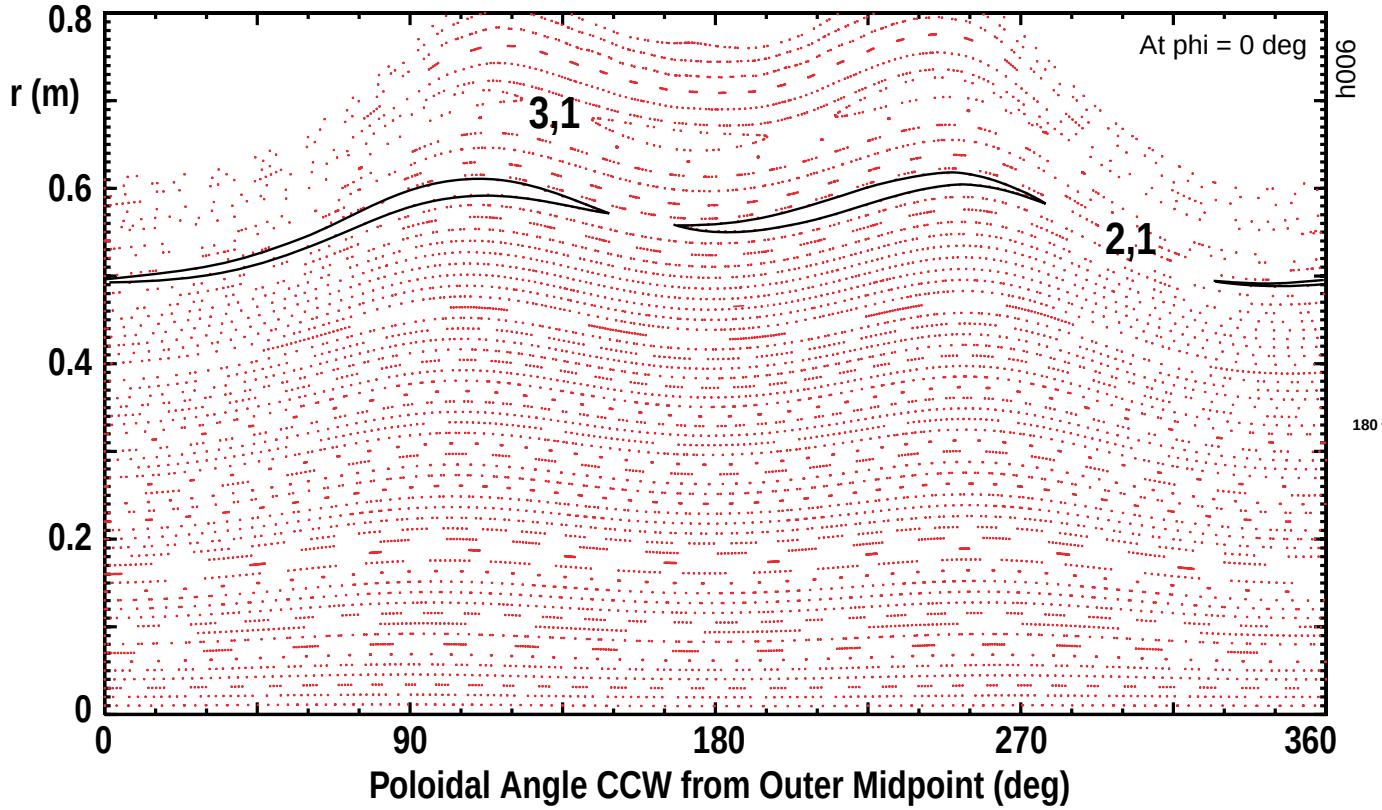
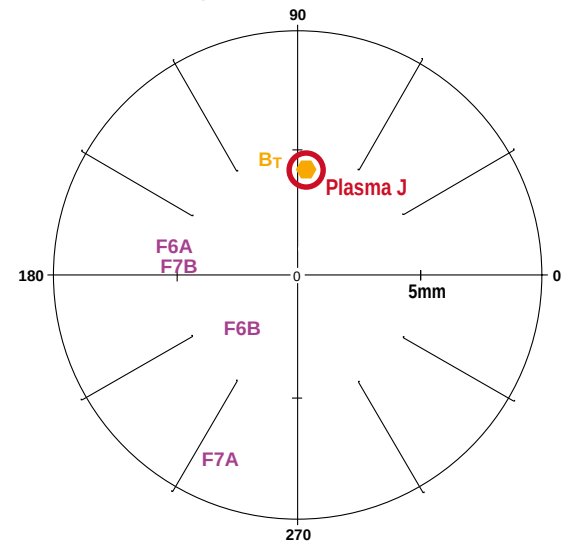
GENERAL ATOMICS

Magnetic Line Tracing Model Results: Off-Center F–Coils Alone Make Modest (≈ 2 cm-wide) 2,1 Islands, if Plasma Current Follows B_T

Plasma Current Centered on B_T. No C-Coil Current.



Coil-Center Locations on Measurement Coordinates



Equilibrium fields are from shot 102115, q(0) ≈ 1.13, Limited, nearly circular (κ ≈ 1.15) for simplicity.

Measured Coil Centers Case: Plasma Current Centered on B_T.
(No C-Coil Current)
(No tilts)

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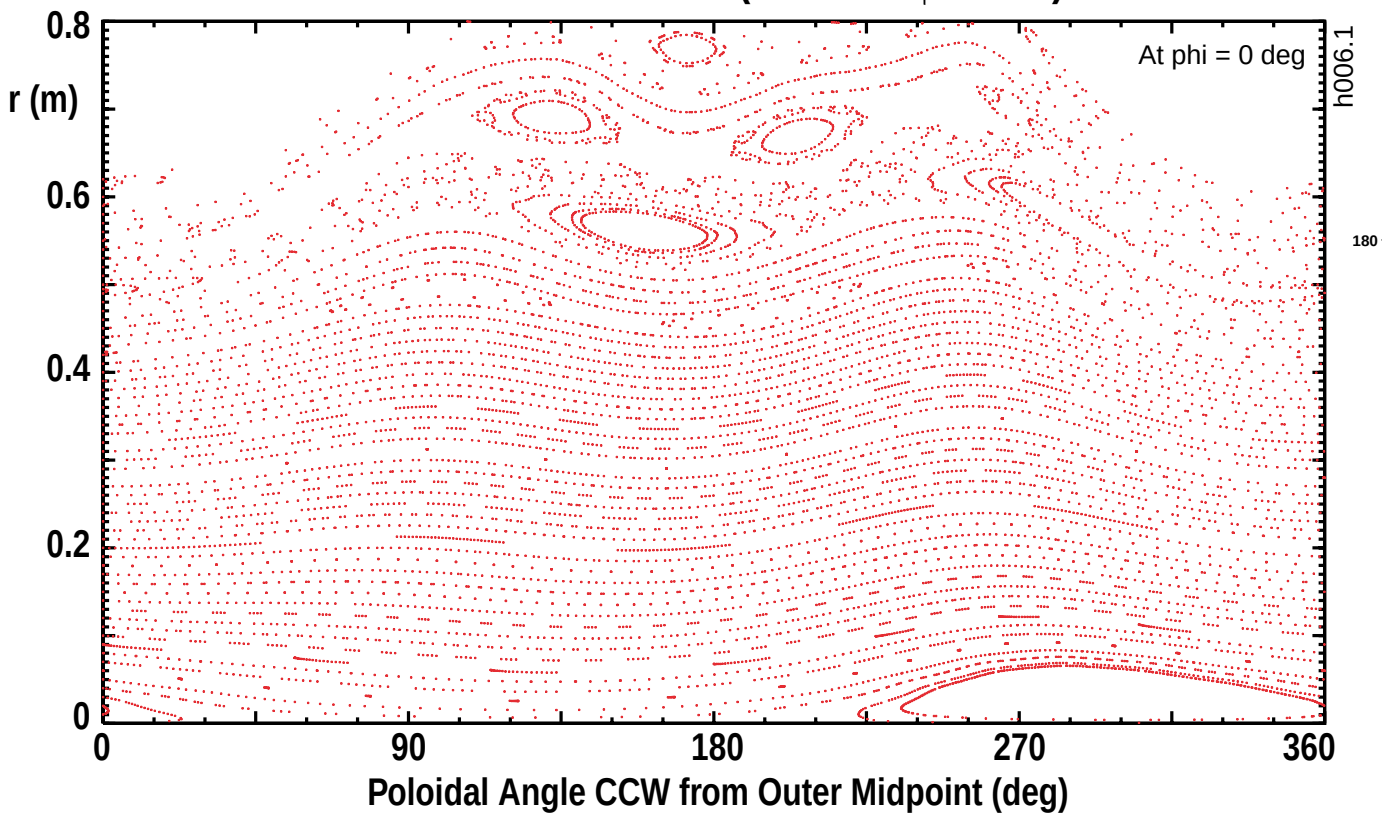
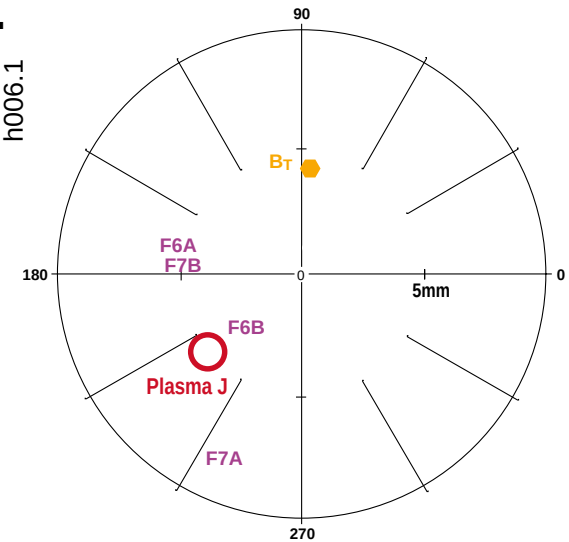
Magnetic Line Tracing Model Results: Off-Center F–Coils Alone Make *LARGE* Islands if Plasma Current Centers on External B_{Pol}

Plasma Current Centered Near F-Coils (5 mm ⇒ ϕ = 220°). No C-Current.





Measured Coil Centers Case: Plasma Current Centered on F-Coils.
(No C-Coil Current)
(No tilts)

- Islands are *MUCH LARGER* if plasma current is centered near F–Coil centers instead of B_T, and Some *surface breakup* is visible.

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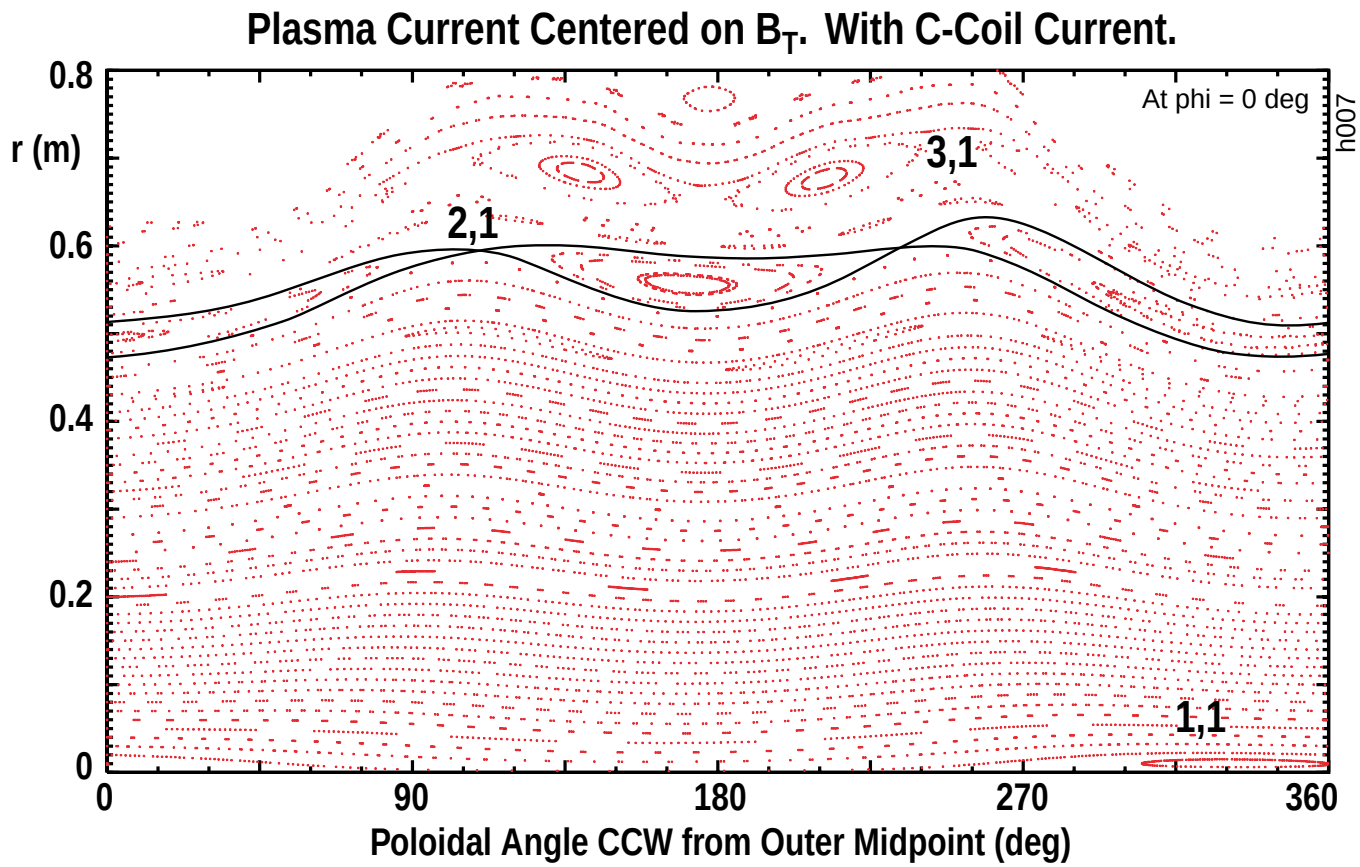
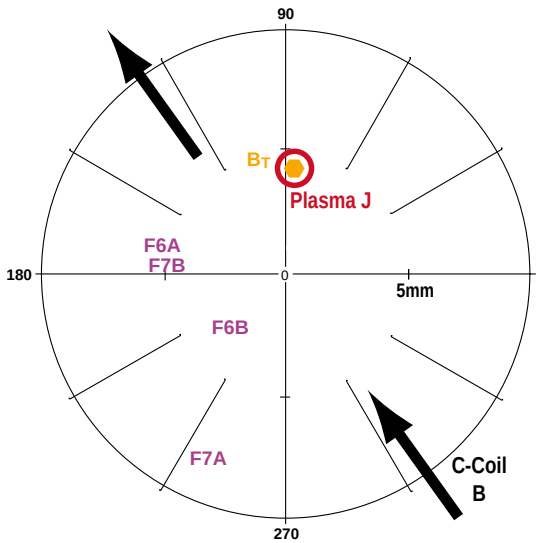
Magnetic Line Tracing Model Results: Adding Experimental C–Coil Field Makes *LARGE* (≈ 6 cm) 2,1 Islands if Plasma Current Follows B_T





Measured Coil Centers.
Case: Plasma Current Centered on B_T, Plus C–Coil Current.
(No tilts)

- It appears that the C–coil *does not* achieve its empirical correction by moving the external poloidal B so that all B and J components are more or less centered on B_T.

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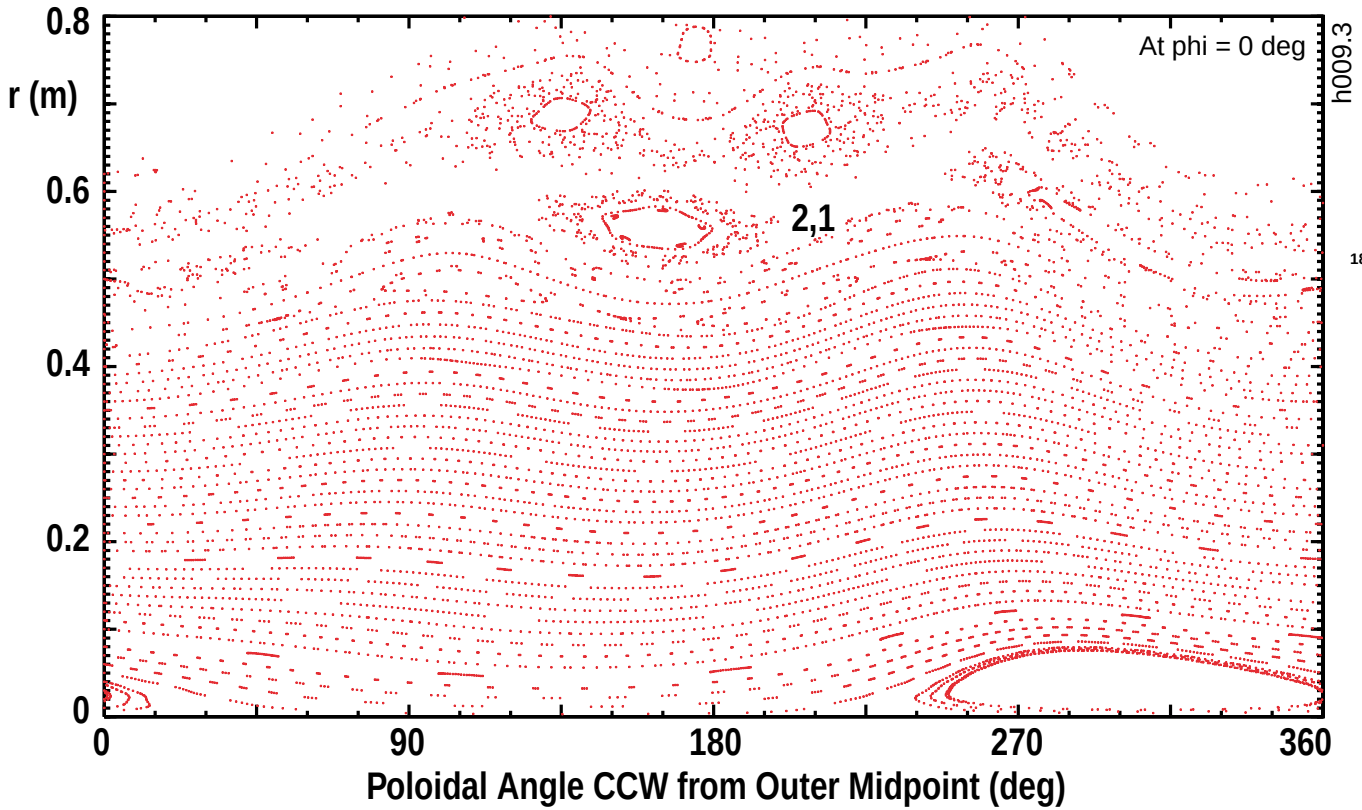
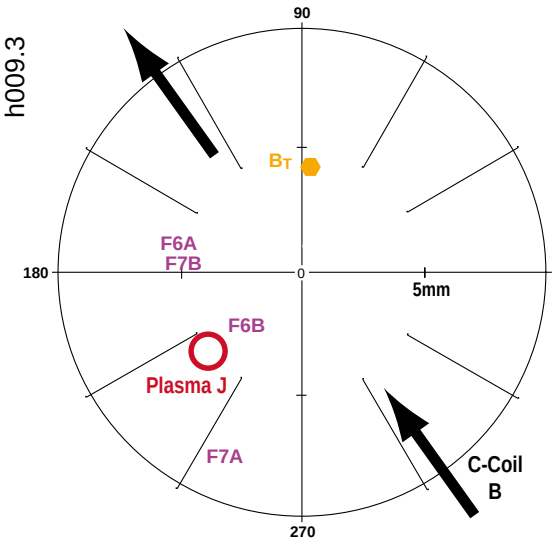
GENERAL ATOMICS

Magnetic Line Tracing Model Results: Adding Experimental C–Coil Field Makes Still *LARGER* Islands if Plasma Current Centers on External B_{Pol}

Plasma Current Centered Near F-Coils (5 mm ⇒ ϕ = 220°). With C-Current.





Measured Coil Centers. Case: Plasma Current Centered on F-Coils, Plus C-Coil Current (No tilts)

- It appears that the C–coil *does not* achieve its empirical correction by moving B_T so that all B and J components are more or less centered on the external poloidal B.

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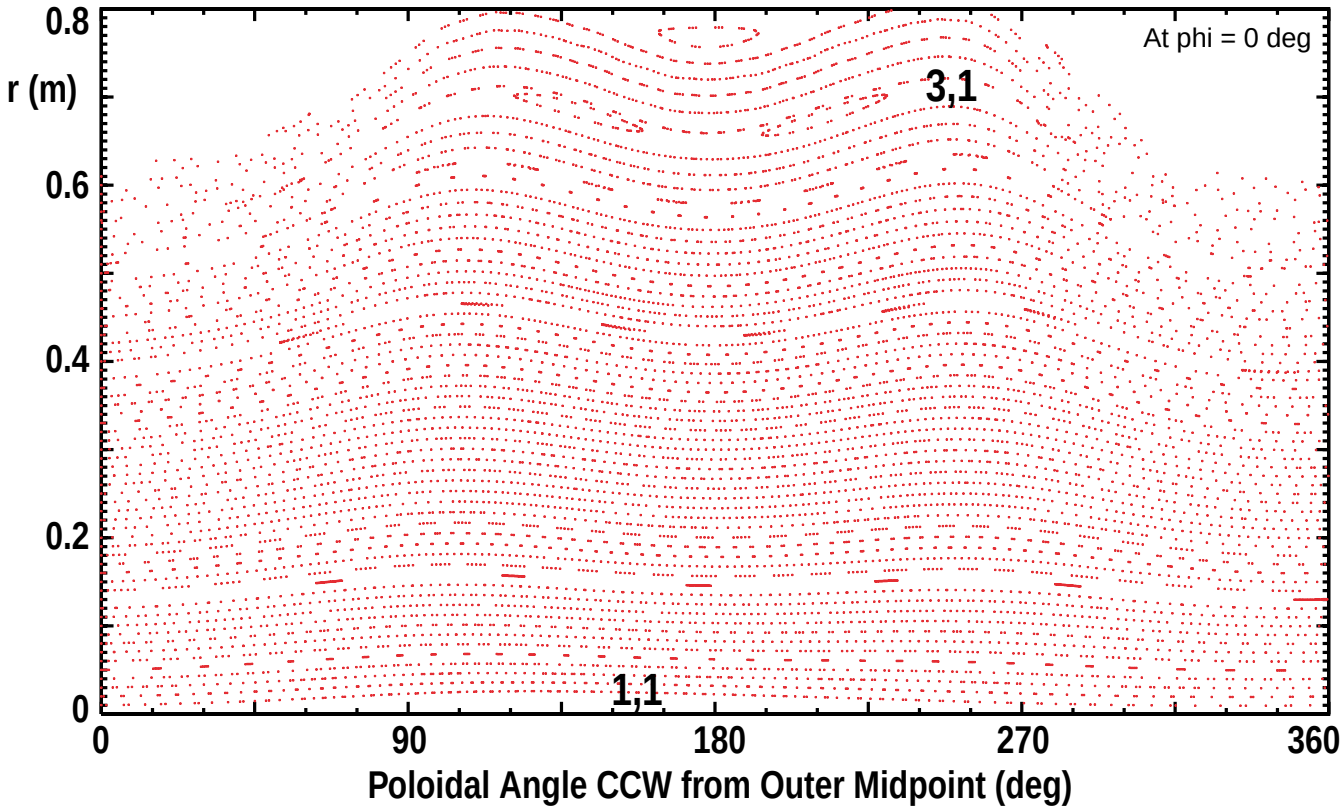
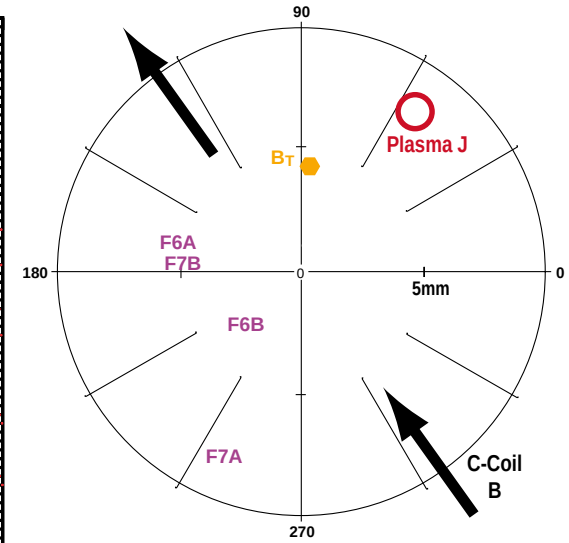
RIGID SHIFT of the Plasma Toroidal Current by ≈ 4.7 mm, 27° from B_T Virtually Eliminates 2,1 Islands in Presence of Experimental C–Coil Field

B_T, F & C-Coils as in Experiment, Plasma Shifted to Minimize 2,1 Islands





F–Coils.
B–Coil.
C–Coil Current.
Case: Shift Plasma Current to get small 2,1 islands.
(No tilts)

- If the C–Coil current minimizes empirical manifestations of islands, it would appear to *push the plasma far from any static B* (if only shifts are considered).

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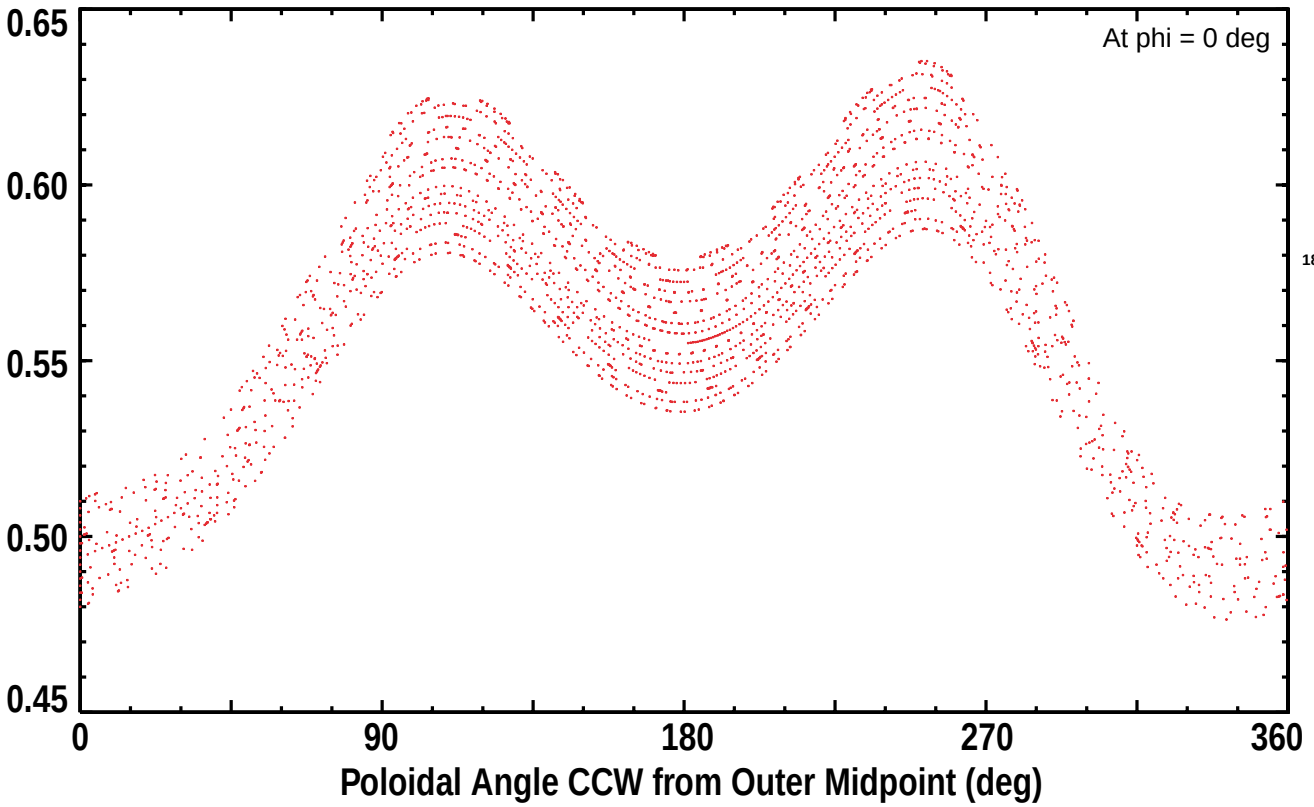
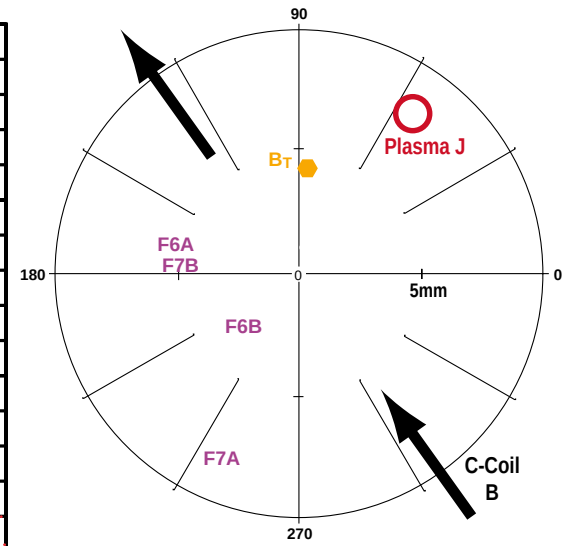
2,1 Island Width with "Optimally" Shifted Current is < 0.5 cm
(Limited by My Patience to do 2–Parameter Scan)

B_T, F & C-Coils as in Experiment, Plasma Shifted to Minimize 2,1 Islands





F–Coils.
B–Coil.
C–Coil Current.
Case: Shift Plasma Current to get small 2,1 islands.
(No tilts)

Expanded view near q = 2 surface of previous slide.

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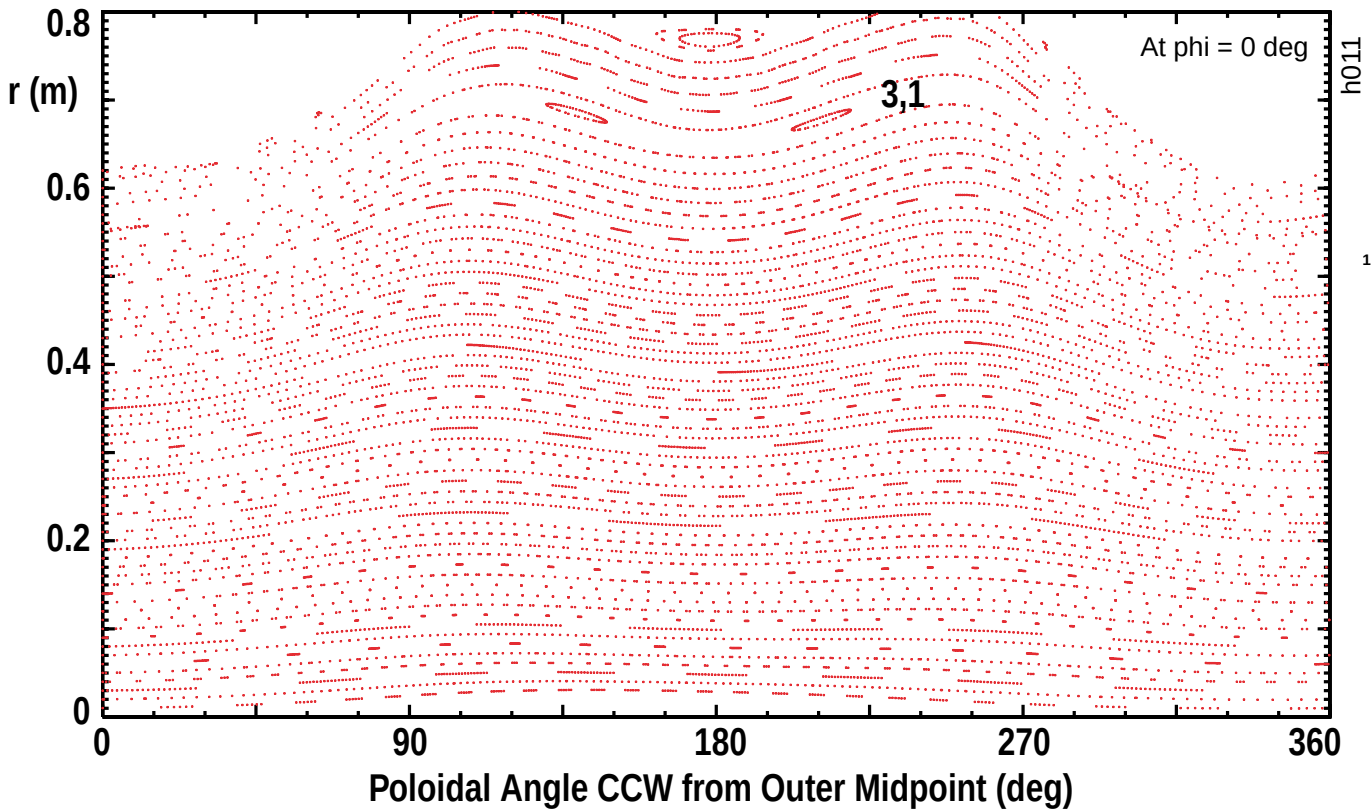
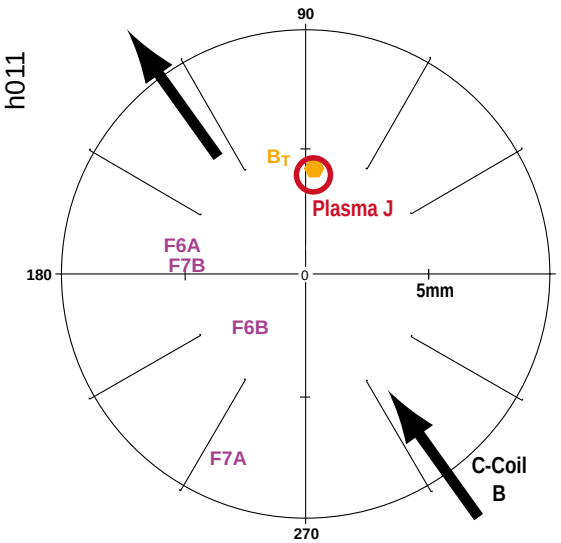
TILT of the Plasma Toroidal Current by 0.0033 rad (5.7 mm at R_o) Reduces 2,1 Islands if Plasma Current Centers on External B_{Pol}

Plasma Current Centered on B_T, Tilted to Reduce 2,1 Islands. With C-Current.





Measured Coil Centers.
Plasma Current
Centered near B-Coil.
C-Coil Current

Case: Tilt Plasma Current to get small 2,1 islands.

- Magnetic surfaces near q = 1 are helically distorted. However, the plasma current tilt found here is approximately opposite to the surfaces' tilt component.
  - Therefore, this arrangement seems inconsistent.

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Discussion

- Presumably, the empirical C–coil correction distorts magnetic surfaces and currents in a self consistent equilibrium way that simultaneously makes magnetic islands small.
- The C–coil field is imperfect…cannot correct all the B error.
  - The C–coil field alone distorts magnetic surfaces near q = 1 helically.
    - A small helical distortion near q = 1 is the same as tilt plus shift.
    - Suggests that the empirically corrected plasmas may be helically (1,1) distorted yet still island-free.
    - Line tracing code just sums specified B-fields; no self consistent equilibrium.
- So far, "pushing the plasma around" to gain insight and to try to find a distorted magnetic shape that seems qualitatively matched to the plasma current has not yielded a candidate "solution".
  - F–coil tilts have not yet been implemented in TRIP3D.
    - But they would add complication rather than insight.

Discussion & Conclusions

- DIII–D magnetic errors were measured well. No large unknown errors discovered.
- The EMPIRICALLY OPTIMIZED C–Coil field INCREASES island size, unless plasma current shifts AWAY from F– and B–Coil centers and/or tilts in response.
  - Is this expected?
  - Maybe. Tilt + Shift ≈ (1,1) helix.
- I claim, "We do not yet understand some important physics feature of the plasma response to magnetic errors."
- We must understand how plasma responds to errors and imperfect corrections, in order to rationally design and operate correction coils in the future.
  - We plan to use MARS code (by Bondeson) to study self-consistent stable 3-D plasma response to external error fields.
    - MARS physics (linearized resistive MHD, plasma rotation, viscous damping) is appropriate for this purpose.

Related Papers at this Meeting

LO1.013 "Modeling 3-D Effects in the DIII-D Boundary," T.E. Evans, R.A. Moyer (UCSD), D. Reiter, S.V. Kasilov (IPP Forschungszentrum Jülich), A.M. Runov (MPI)

QP1.072 "3-D Equilibrium and Magnetic Island due to Error Magnetic Field in the DIII-D Tokamak," L.L. Lao, M.S. Chu, M.J. Schaffer, R.J. La Haye, T.E. Evans (General Atomics), K.I. You (KBSI), E.A. Lazarus, S.P. Hirshman (ORNL)

QP1.077 "Investigation of Resonant and Non-resonant Magnetic Braking in Plasmas Above the No-Wall Beta Limit," J.T. Scoville, E.J. Strait, R.J. La Haye (General Atomics), A.M. Garofalo, H. Reimerdes (Columbia U.), M. Okabayashi (PPPL)

QP1.080 "Modeling and Design of a Resistive Wall Mode Stabilization System With Internal Field Coils in DIII-D,"G.L. Jackson, A.G. Kellman, P.M. Anderson, R.J. La Haye, A. Nerem, J.T. Scoville, E.J. Strait (General Atomics), G.A. Navratil, J. Bialek, A.M. Garofalo, H. Reimerdes, (Columbia U.), R. Hatcher, L.C. Johnson, M. Okabayashi (PPPL)

QP1.081 "Critical Rotation for Stabilization of n=1 Ideal Kink (Resistive Wall Mode) in DIII-D," R.J. La Haye, M.S. Chu, E.J. Strait (General Atomics), A.M. Garofalo, H. Reimerdes (Columbia U.), M. Okabayashi (PPPL)

QP1.082 "Feedback Stabilization of the Resistive Wall Mode in Low-Rotation DIII-D Plasmas," M. Okabayashi, L.C. Johnson (PPPL), J. Bialek, A.M. Garofalo, G.A. Navratil, H. Reimerdes (Columbia U.), R.J. La Haye, J.T. Scoville, E.J. Strait, DIII-D Team (GA)

QP1.083 "Active Measurement of the Resistive Wall Mode Stability in Rotating DIII-D Plasmas," H. Reimerdes, A.M. Garofalo, G.A. Navratil (Columbia U.), M.S. Chu, G.L. Jackson, T.H. Jensen, R.J. La~Haye, J.T. Scoville, E.J. Strait (GA), L.C. Johnson, M., Okabayashi (PPPL)

QP1.084 "Effects of Plasma Rotation and Dissipation on Resistive Wall Mode in Tokamaks," Y.B. Kim, D.H. Edgell, I.N. Bogatu, J.S. Kim (FARTECH)

RP1.046 "Evidence for Stochastic Effects in the DIII-D Boundary," R.A. Moyer (UCSD), T.E. Evans (GA), T.L. Rhodes (UCLA), J.G. Watkins (SNL), C.J. Lasnier (LLNL), H. Takahashi (PPPL)