SEPARATRIX LOCATION AND ERROR FIELD

L.L. Lao, D.P. Brennan, M.S. Chu, T.E. Evans, R.J. La Haye, J.L. Luxon, T.C. Luce, T.W. Petrie, M.J. Schaffer, E.J. Strait, T.S. Taylor, M.R. Wade,[1] and K.I. You[2]

General Atomics, San Diego, CA, U.S.A.
[1]Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A.
[2]Korea Basic Science Institute, South Korea

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MOTIVATION / BACKGROUND

- Enhanced confinement of H-mode discharges often leads to large edge density and temperature pedestals with very narrow widths ~ 1-4 cm
- Accurate determination of the edge separatrix location becomes crucial for proper interpretation and understanding of the physical processes governing H-mode discharges
- In DIII-D, a 1-4 cm difference is found between the separatrix vertical position determined from EFIT magnetic analysis and those inferred from Thomson T_e measurements
  - First seen in some quiescent H-mode (QH-mode) upper single-null discharges but since found also exist for other discharges

QUESTIONS TO ANSWER

- Are the difference between the edge separatrix vertical positions as determined from EFIT and Thomson T_e due to real physical effects ?
- What physical processes may lead to this difference ?
- What are the effects of externally imposed toroidally asymmetric magnetic field or error magnetic field on the edge separatrix boundary ? The new I-coils ?
- How important are the plasma responses ?

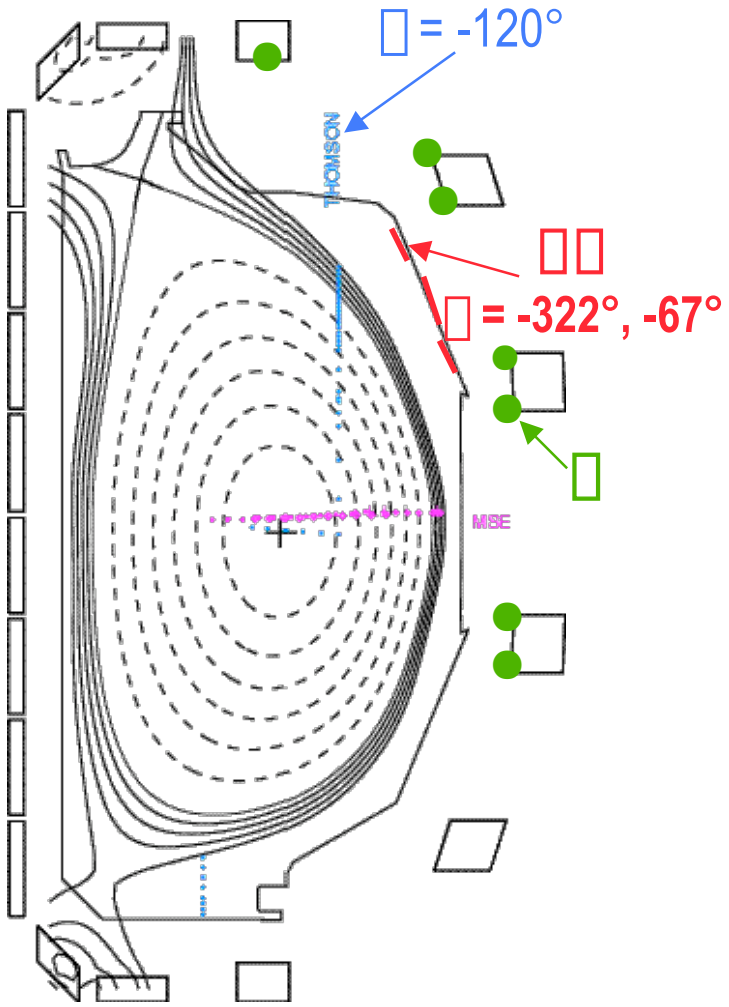
12-coil internal set available for experiments 2003

OUTLINE / SUMMARY

- Separatrix location can be conveniently obtained from EFIT magnetic analysis and inferred from Thomson T_e measurements in H-mode discharges
- Results from the two methods generally agree for lower single-null discharges
- There can be a 1-4 cm difference in the Thomson separatrix vertical position in upper single-null and double-null discharges when B_P is weaker near the Thomson viewing path
- Results of an heat flux analysis for a upper single-null discharge are consistent with a 1-2 cm difference seen between EFIT and Thomson
- A leading explanation for this difference is the toroidal asymmetry due to external magnetic field
- Perturbative 3-D calculations indicate a 1-2 cm radial shift in the external coil location can lead to formation of an edge ergodic layer with observable distortion of the plasma shape
  - Need to include plasma response

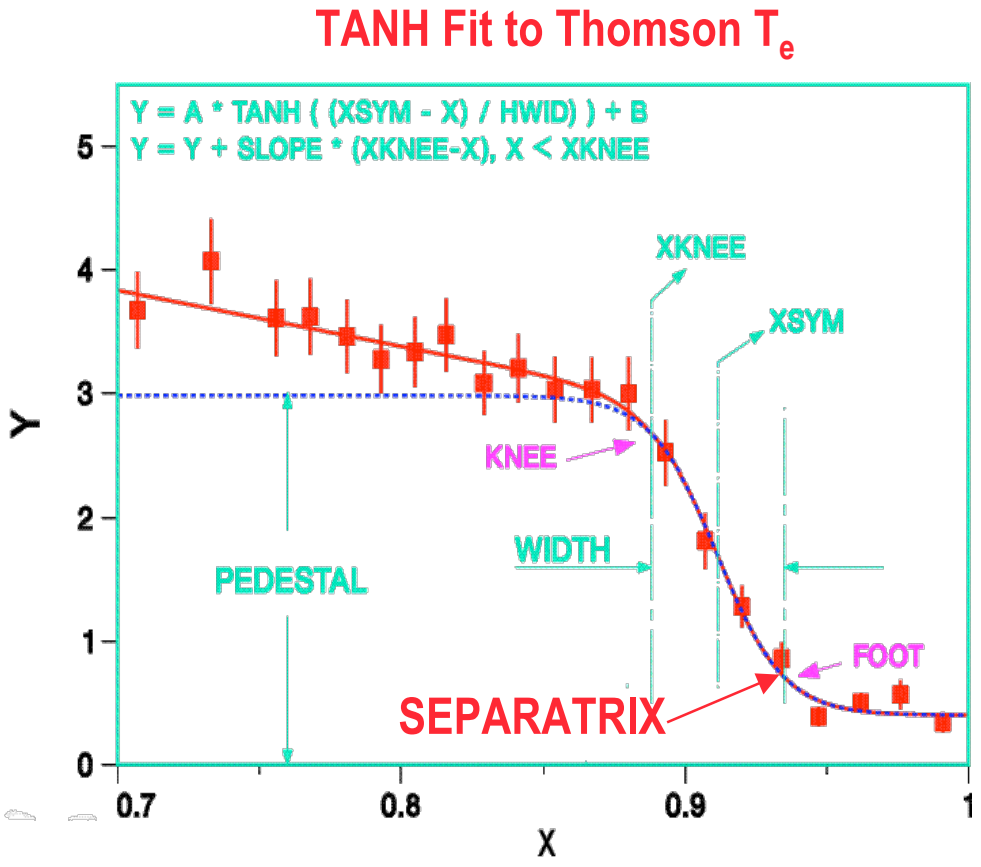
SEPARATRIX LOCATION IS DETERMINED BY EXTRAPOLATING EXTERNAL MAGNETIC MEASUREMENTS INWARD

- EFIT extrapolates magnetic measurements inward assumed discharge in a 2-D equilibrium state
  - ~ 41 flux loops: □, ~ 73 magnetic probes: □□
  - Equilibrium relates 2nd derivatives to □ and □□
  - Separatrix location defined by largest closed flux surface enclosed by limiter
  - More accurately determined if separatrix is closer to magnetic loops
- Main magnetic probes are at □ = -322°, some at -67°
  - Separatrix location largely represents magnetic topology at □ = -322°
- Thomson measurements are at □ = -120°



SEPARATRIX LOCATION CAN ALSO BE INFERRED FROM HYPERBOLIC TANGENT FIT TO THOMSON T_e PROFILE

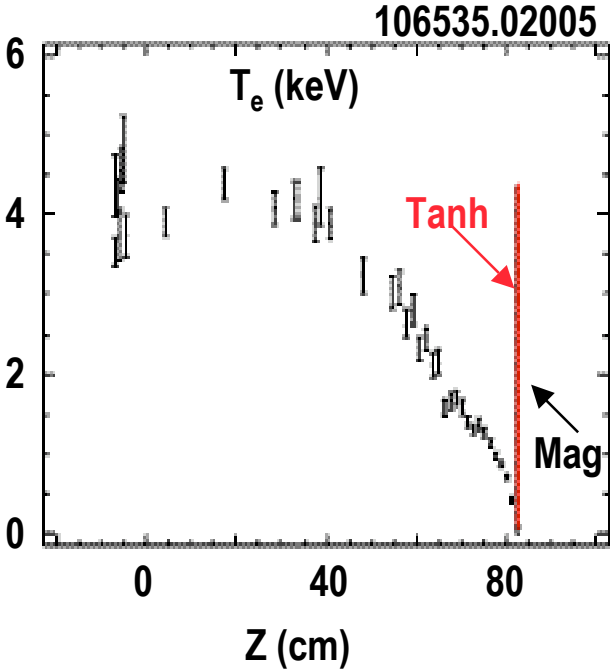
- H-mode discharges only
- 3 parameters amplitude, radius, and width Tanh fit to T_e
- $Z_{TS} = Z_{SYN} + 0.5 \Delta Z_{WIDTH}$
- Previous analyses indicate some consistency with UEDGE divertor heat flux solution with this approach [1]
- Thomson measurements are located at the poloidal plane $\phi = -120°$

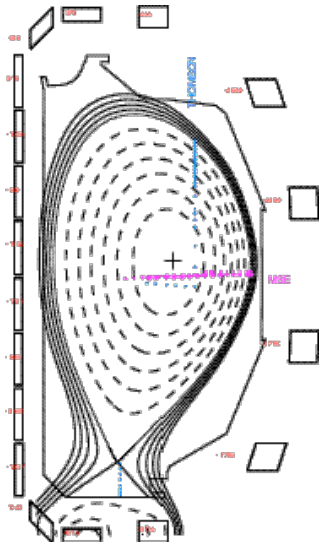


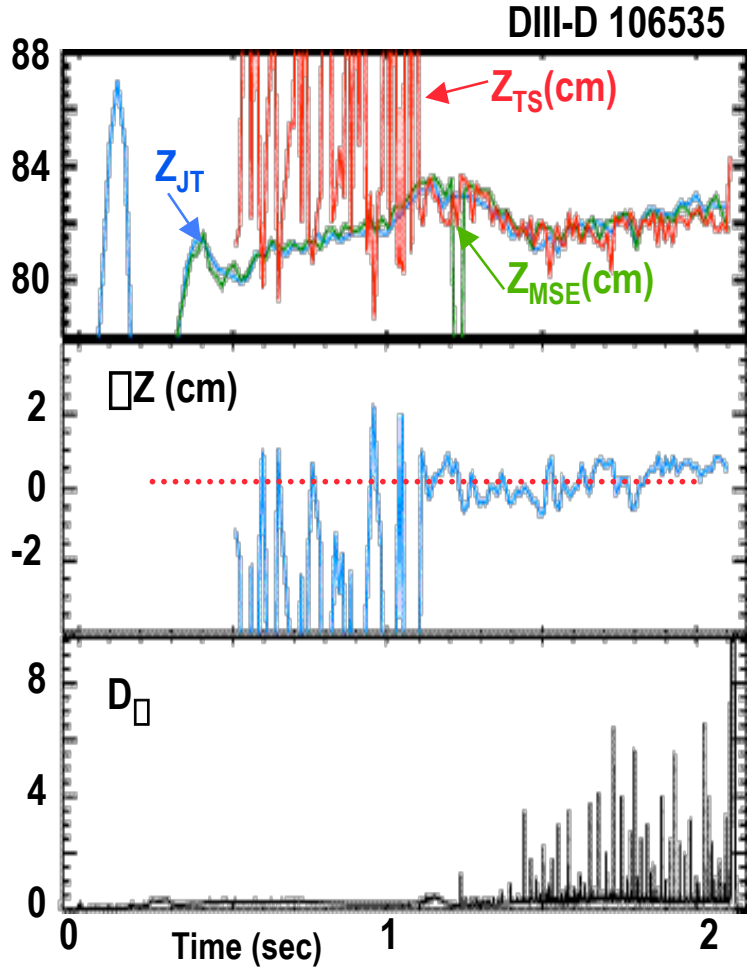
[1] Porter, 1998 Phys. Plasmas **5** 1410

SEPARATRIX LOCATIONS FROM EFIT AND THOMSON AGREE IN LOWER SINGLE-NULL DISCHARGES

- From 2001 resistive wall mode stabilization experiment

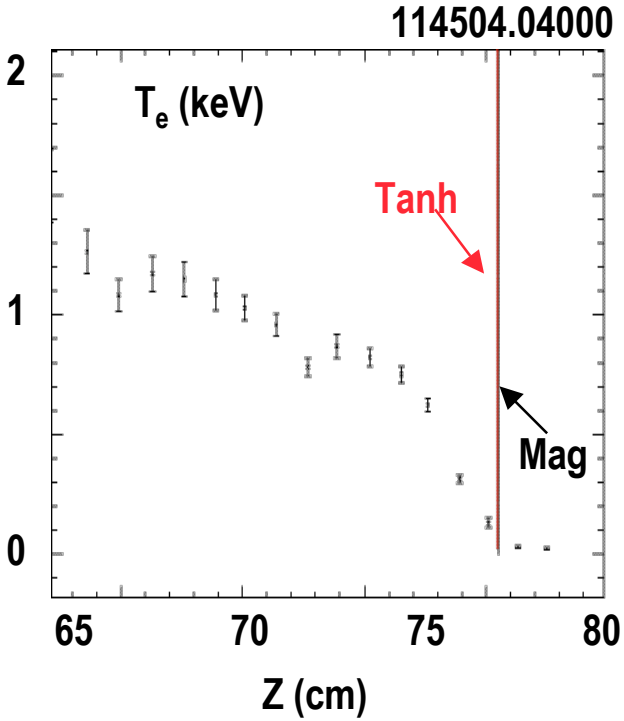


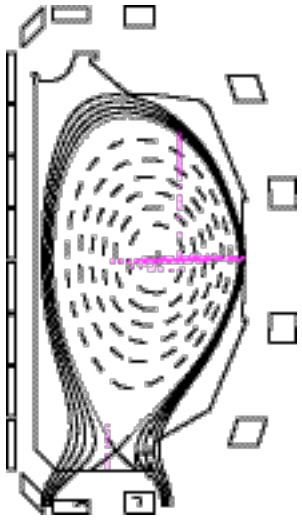


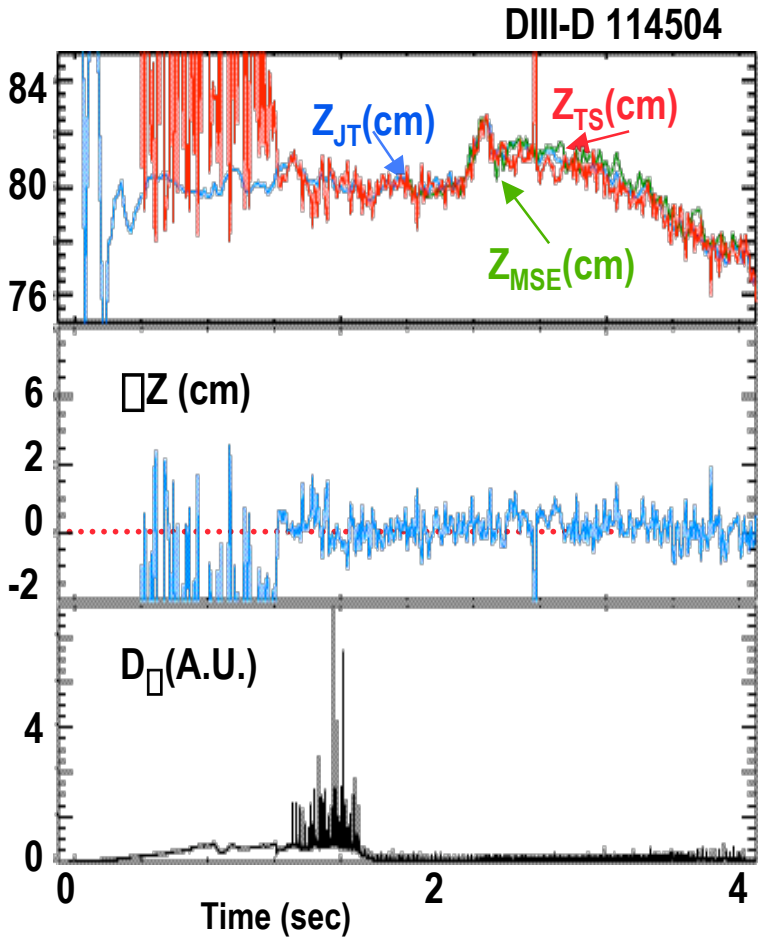


SEPARATRIX LOCATIONS FROM EFIT AND THOMSON AGREE IN LOWER SINGLE-NULL DISCHARGES

- From 2003 NTM active tracking ECH stabilization experiment

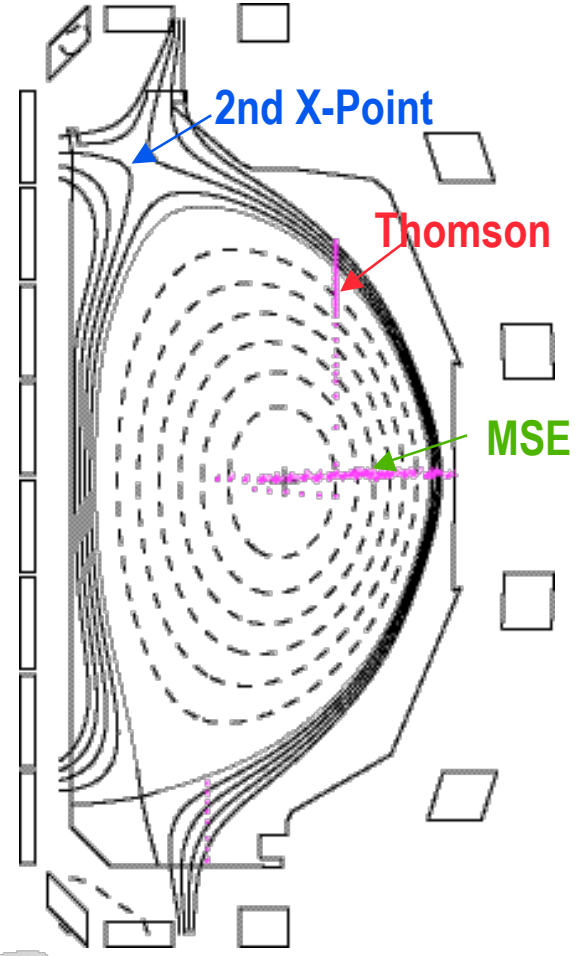






SEPARATRIX LOCATIONS FROM EFIT AND THOMSON CAN DIFFER WHEN EXTERNAL X-POINT IS CLOSER

- From 2003 ergodic edge ELM experiment Evans
- Similar □Z's with or without I-Coil



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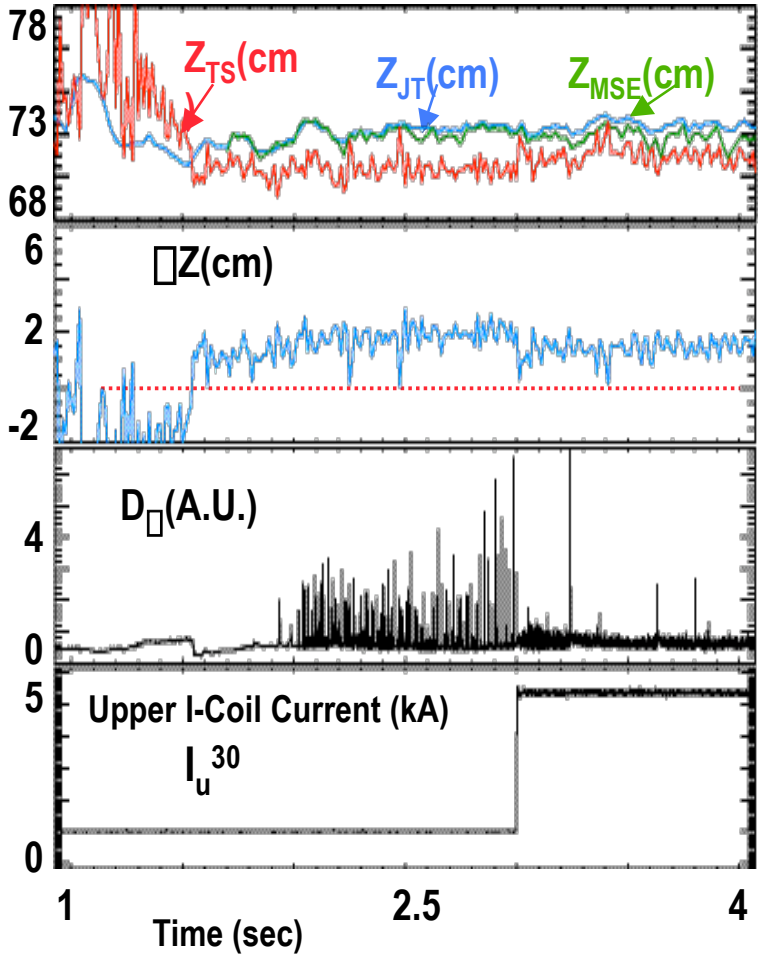

HIGHER χ^2_{MAG} WHEN EQUILIBRIUM RECONSTRUCTED WITH THOMSON SEPARATRIX CONSTRAINT

- From 2003 ergodic edge ELM experiment Evans
- Reconstructions using for vertical position switch option improve convergence

	Iterations	Convergence Error	χ^2_{MAG}	Z_{JT}(cm)
No I-Coil 2900 ms	42	8.1×10^{-5}	9.2	72.5
No I-Coil Fit ΔZ	10	7.6×10^{-5}	9.1	72.5
No-Icoil Fit Z_{TS}	36	9.4×10^{-5}	14.6	70.6
I-Coil 3400 ms	28	9.3×10^{-5}	9.5	72.9
No I-Coil Fit ΔZ	11	6.4×10^{-5}	8.6	72.9
No-Icoil Fit Z_{TS}	29	7.4×10^{-5}	10.3	71.9

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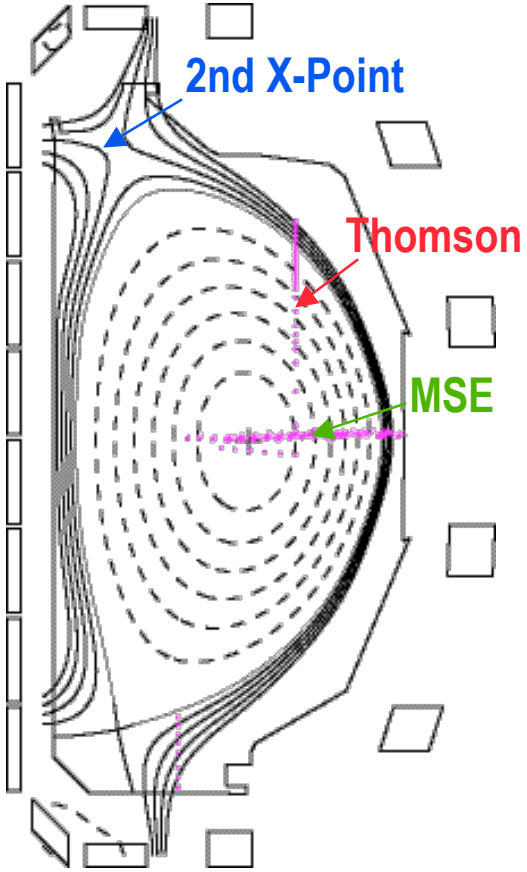
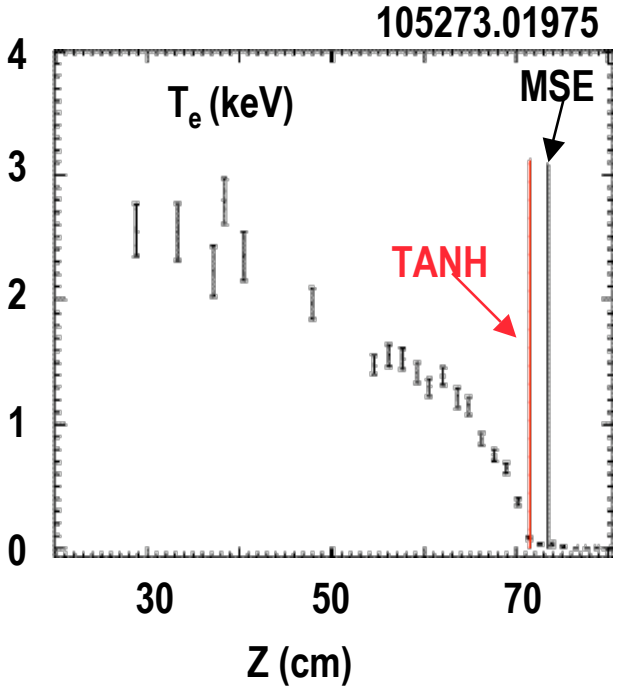
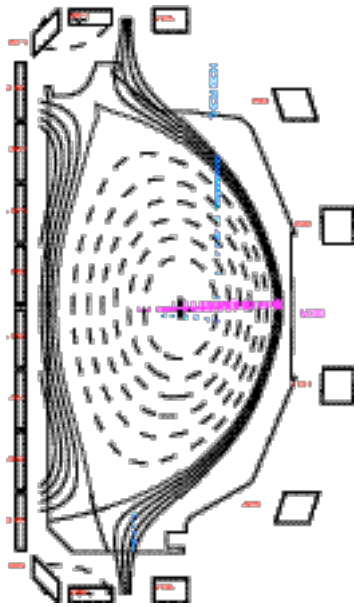
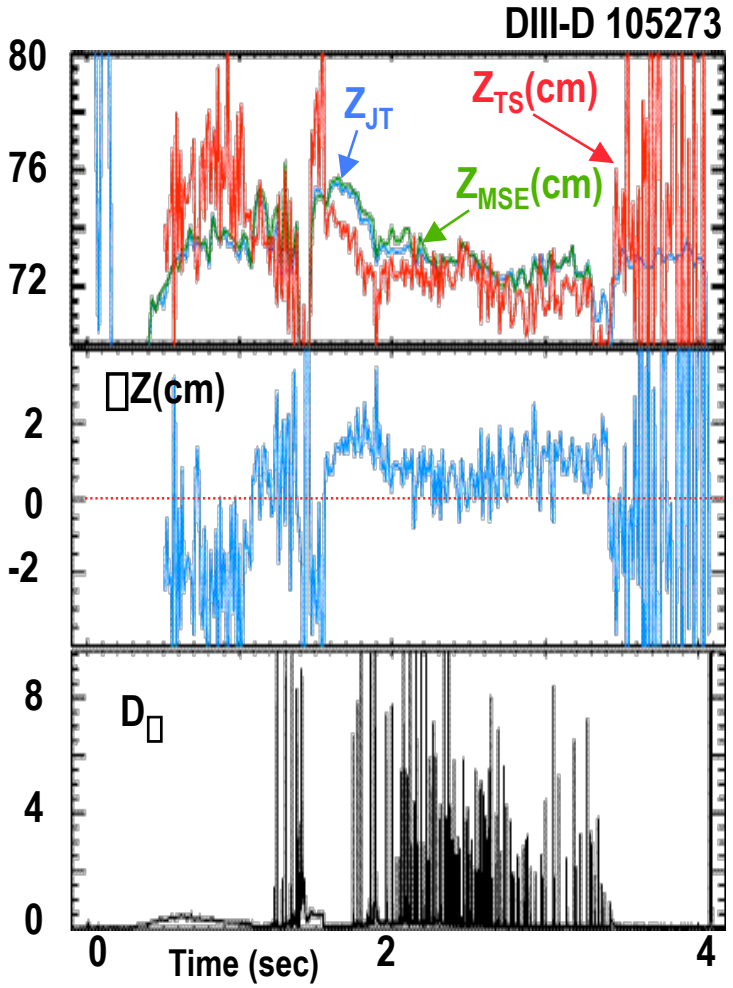


SEPARATRIX LOCATIONS FROM EFIT AND THOMSON CAN DIFFER BY 1-2 cm IN DOUBLE-NULL DISCHARGES

- From AT stability experiment, $\beta_N \sim 4$, $q_{95} \sim 4.2$

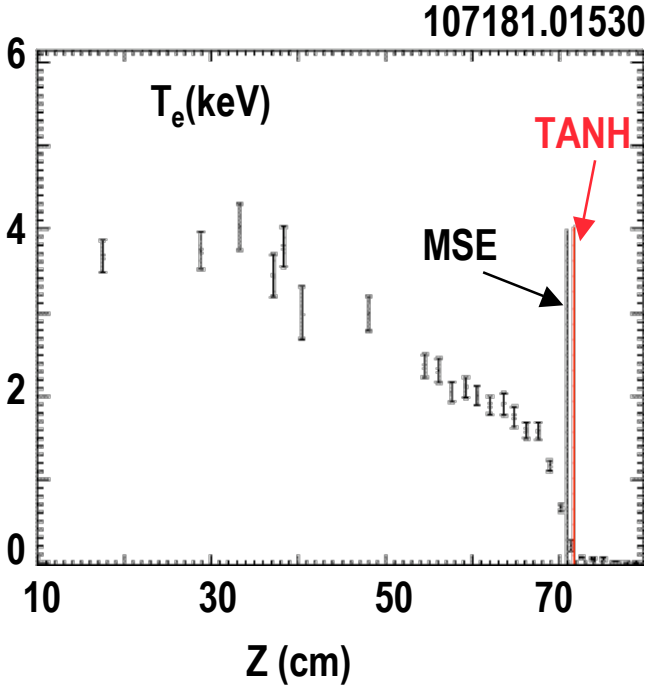


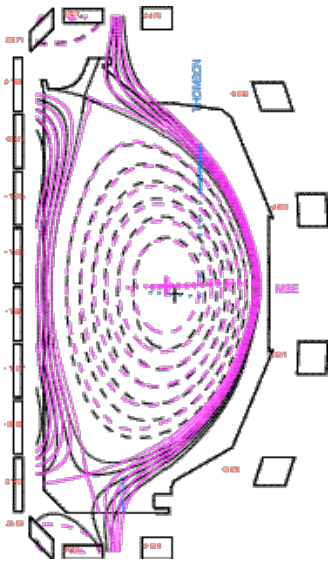


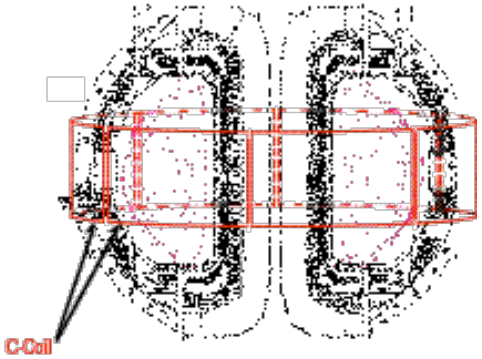


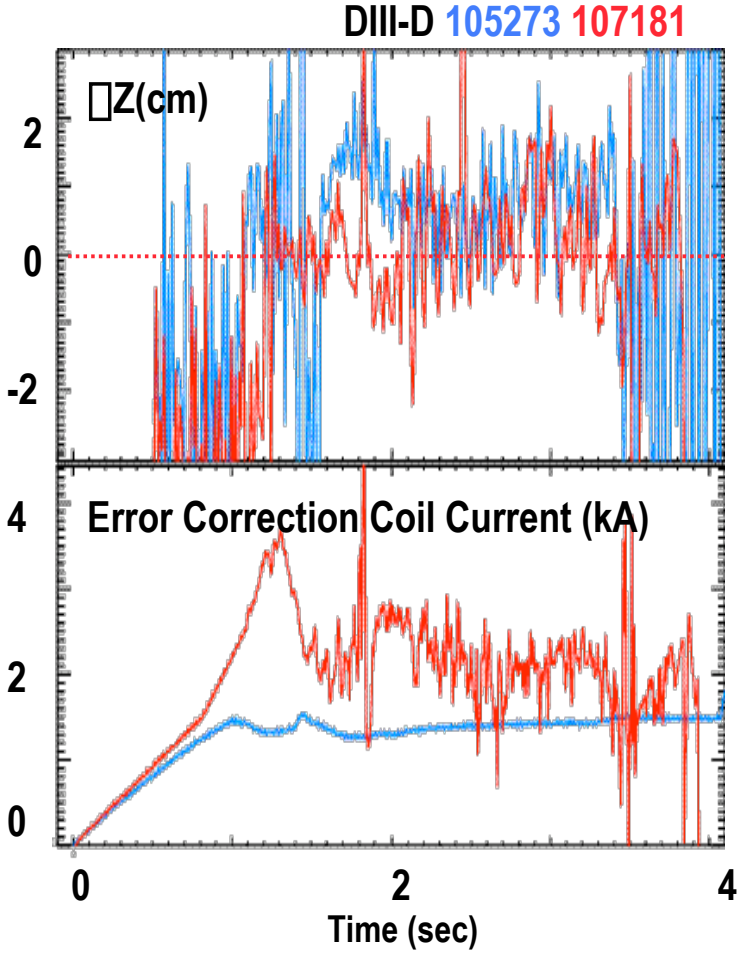
ERROR FIELD CORRECTION COIL CURRENT APPEARS TO PLAY A ROLE IN THE EFIT-THOMSON SEPARATRIX LOCATION DIFFERENCE

- From AT stability experiment, β_N ~ 3.8, q_{95} ~ 5.1, higher C_{79} current



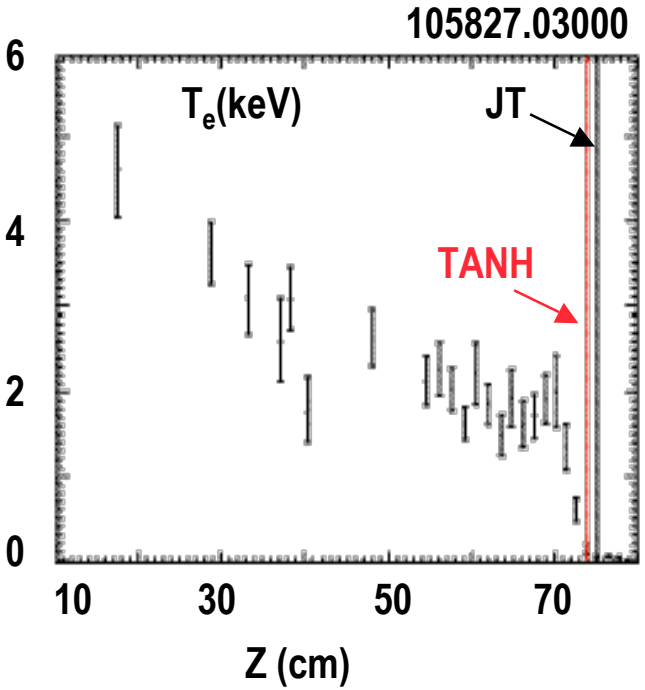


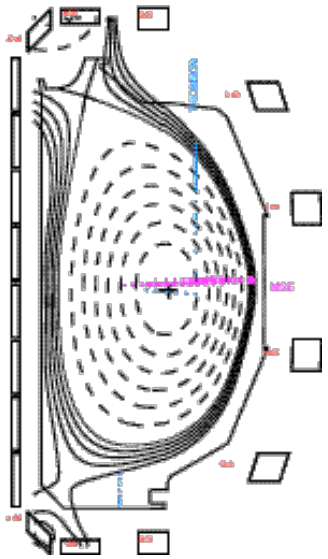


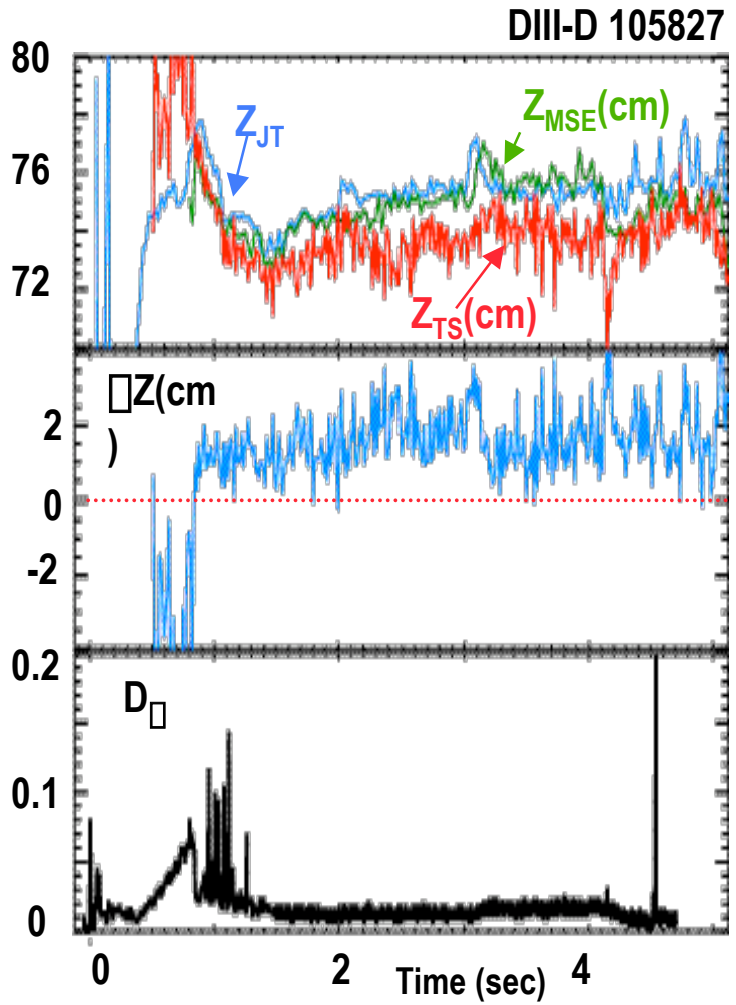


SEPARATRIX LOCATIONS FROM EFIT AND THOMSON CAN DIFFER BY 1-4 cm IN UPPER SINGLE-NULL DISCHARGES

- From 2001 QH mode experiment using 1.3 MA shape control panel

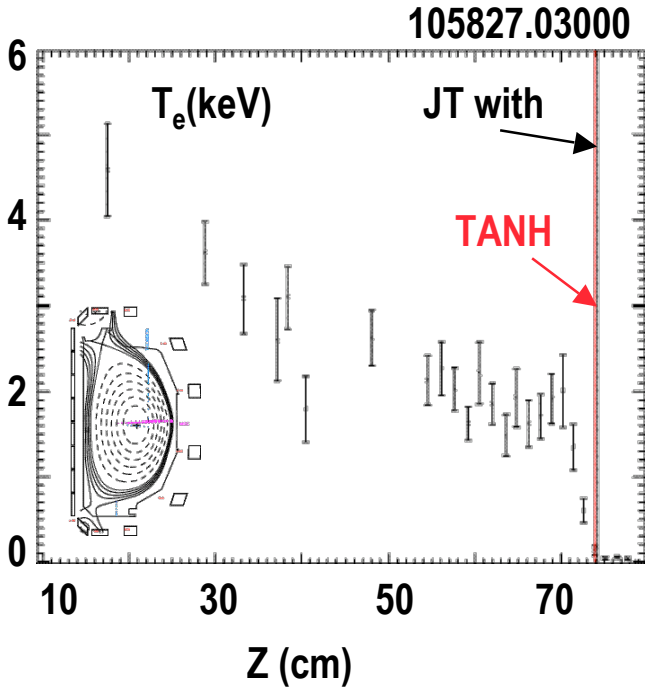


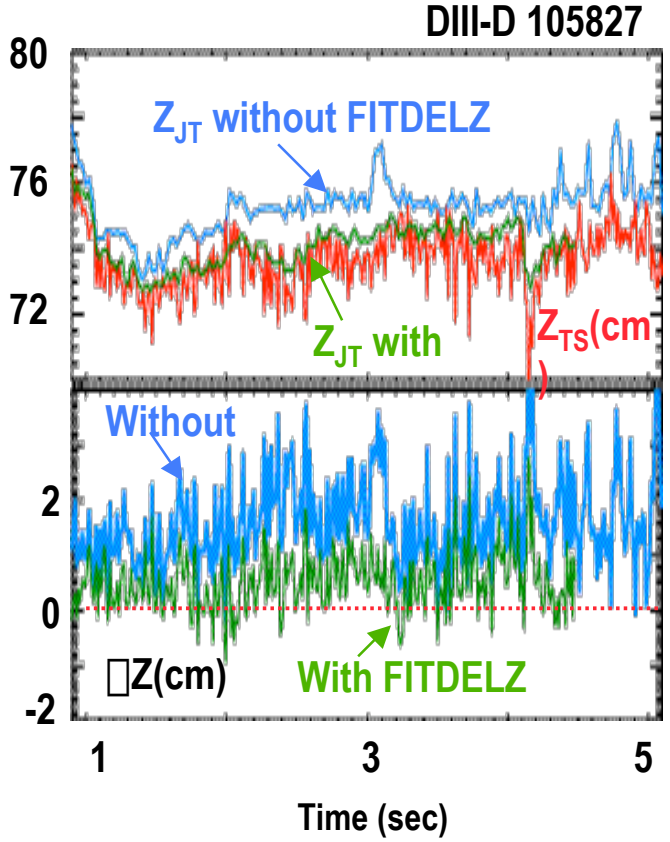




VERTICAL POSITION FITTING SWITCH SOMETIMES HELPS FINDING A BETTER NUMERICAL SOLUTION

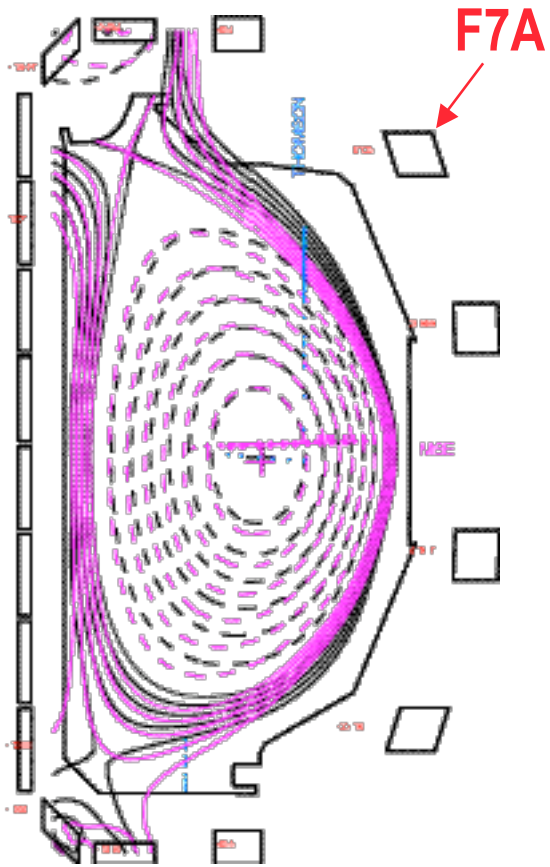
- From 2001 QH mode experiment using 1.3 MA shape control panel
- Z dependence only enters Grad-Shafranov equation implicitly
- ψ is allowed to have a rigid body shift during iteration $\psi^{n} = \psi^{n-1} + \Delta Z \, \psi_Z^{n-1}$
- When effective both χ^2 and convergence are usually improved

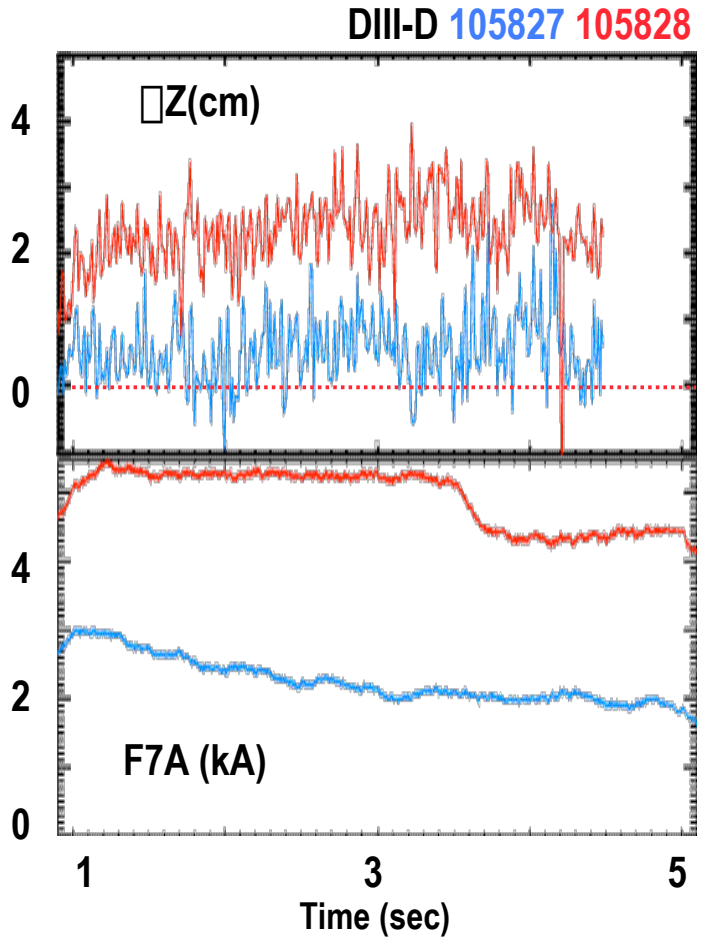




CURRENT IN F7A APPEARS TO PLAY A ROLE IN THE EFIT-THOMSON SEPARATRIX LOCATION DIFFERENCE

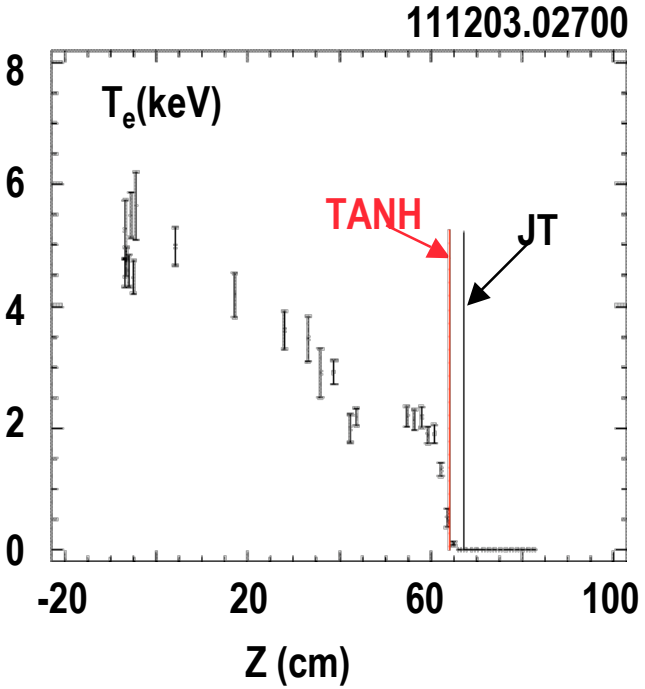
- From 2001 QH mode experiment using 1.3 MA and 1.6 MA panels

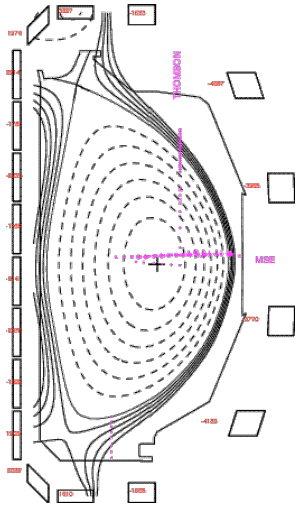


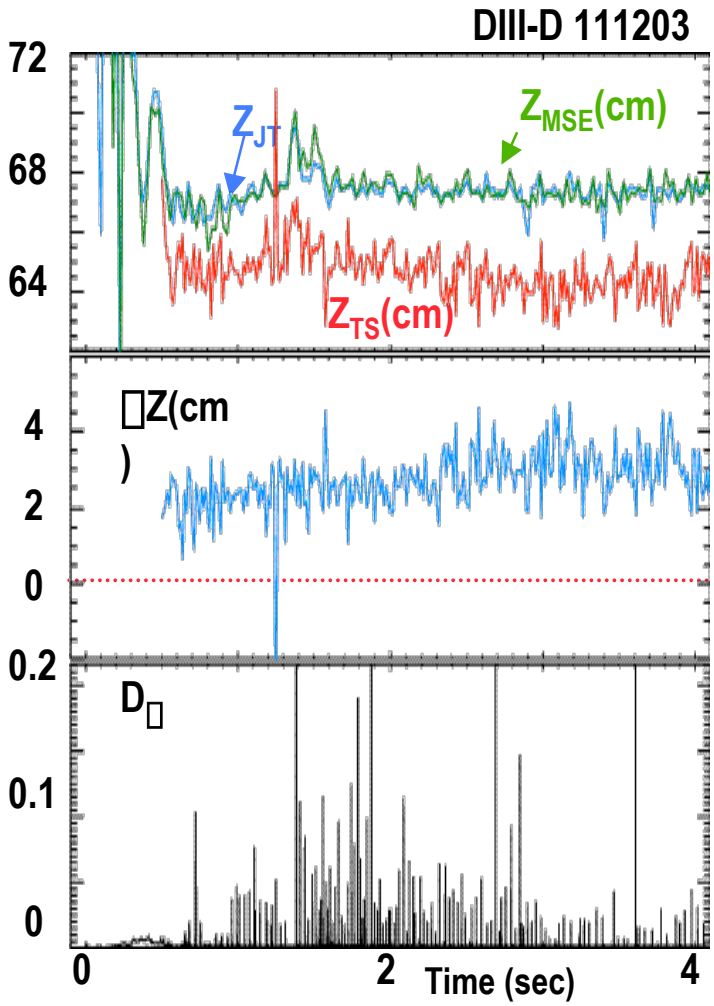


SEPARATRIX LOCATIONS FROM EFIT AND THOMSON CAN DIFFER BY 1-4 cm IN UPPER SINGLE-NULL DISCHARGES

- From 2002 AT ECCD experiment
- Metal plate on n1-coil has been removed but makes little difference





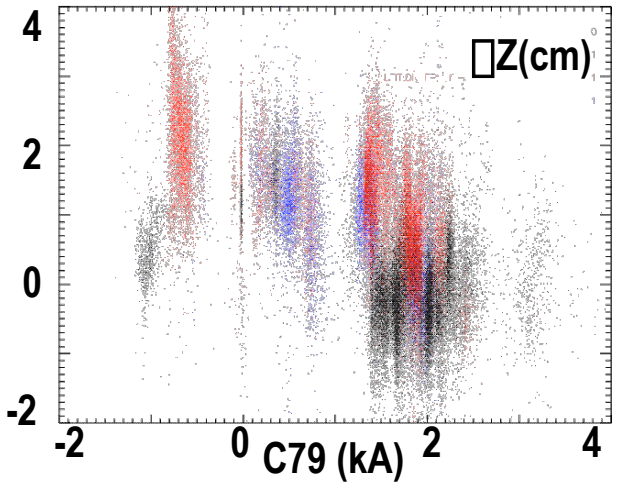


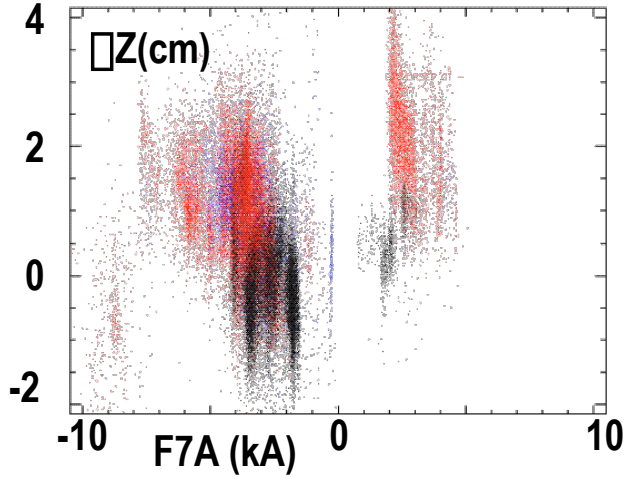
DATABASE SURVEY

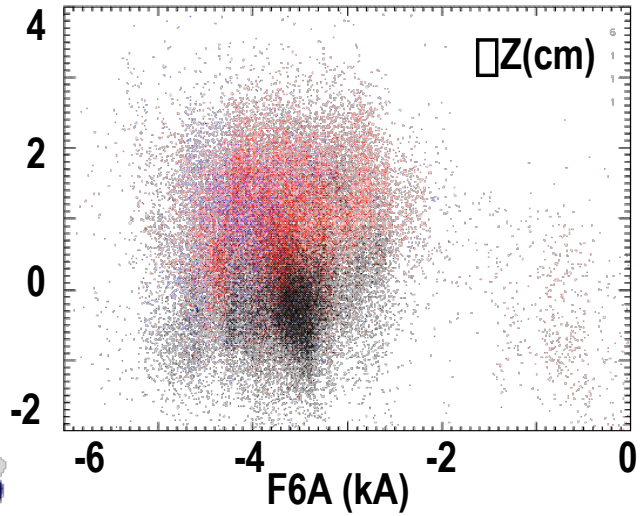
- Shot range ~ 97600 - 105500, 1999 - early 2001 using an IDL code
- H-mode only with 1 sec < time < 4 sec (based on electron edge pedestal height and width) and JT-like control room EFITs (EFIT01), sorted by
  - Lower single null (LSN), $\Delta R_{SEP} < -1$ cm
  - Double null (DND), $-1 \text{ cm} < \Delta R_{SEP} < 1$ cm
  - Upper single null (USN), $\Delta R_{SEP} > 1$ cm
- EFIT-Thomson separatrix difference generally within acceptable bound for LSN, but can differ by 1-4 cm in DND and USN cases
  - No correlation with electron edge pedestal pressure, β_P and β_N, lower triangularity
  - Weak correlation with upper triangularity and l_i
  - Some correlation with F7A and C-Coil currents, and q_{95}

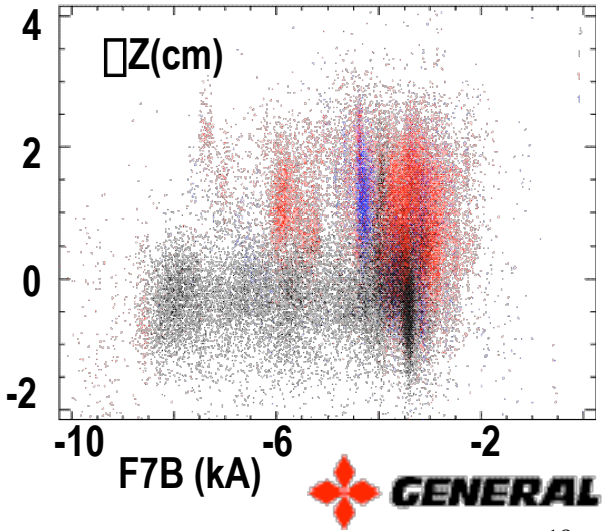
DATABASE SURVEY INDICATES SOME CORRELATION WITH CURRENTS IN F7A AND C-COIL

- Main sorting variables: DND, USN, and LSN. H-mode only, 1999 - early 2001









DIVERTOR HEAT FLUX ANALYSIS

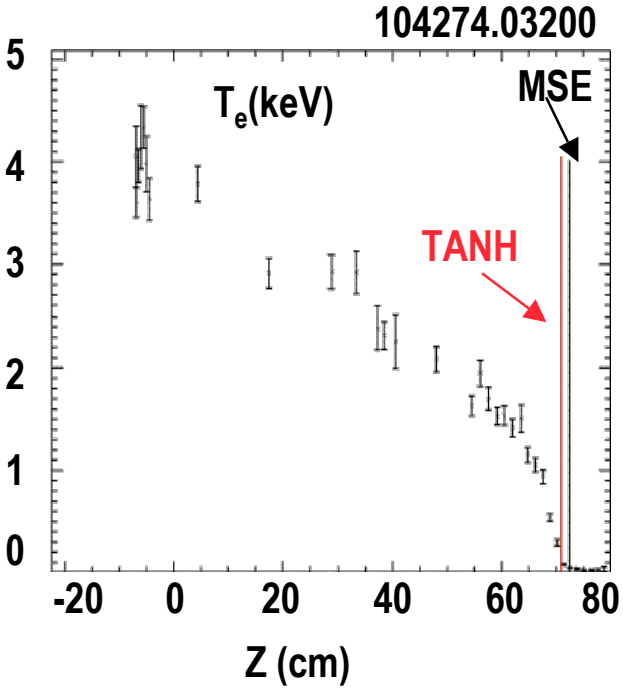
- To determine if the upstream T_e along the separatrix implied by the IR camera heat flux measurement (θ ~ -225 °) is consistent with that from Thomson scattering based on EFIT mapping
- Approach
  - Use upper single-null discharge 104274 from a 2001 AT experiment
  - Assumed SOL in sheath-limited regime

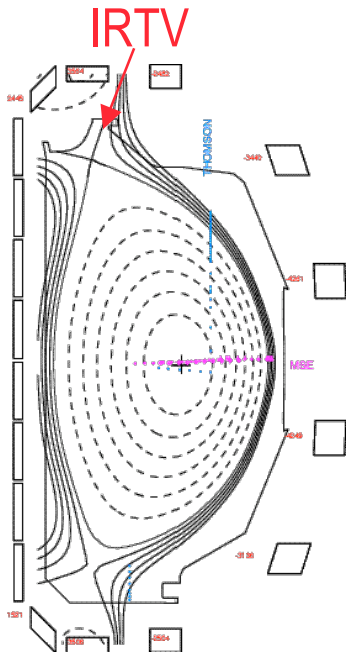
$$n_{eu} \approx \frac{18.2 x q_{\theta}}{\gamma x [T_{eu}]^{1.5} \; x\{1 + \frac{T_{iu}}{T_{eu}}\}^{0.5} x [\frac{B_z}{B}]_t}$$

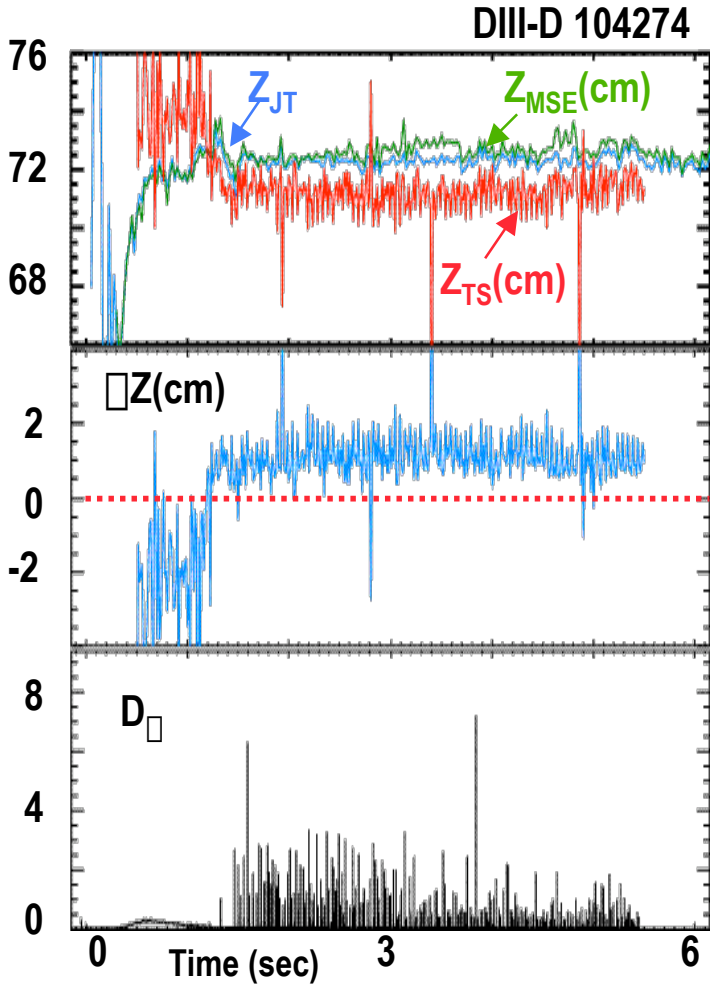
  - γ = sheath heat transmission coefficient
  - Assume peak q_{θ} is at separatrix location

SEPARATRIX LOCATIONS FROM EFIT AND THOMSON DIFFER BY ~ 1-2 cm IN THIS USN DISCHARGE

- From 2001 AT experiment, $\beta_N \sim 2.7$, $q_{95} \sim 4.3$



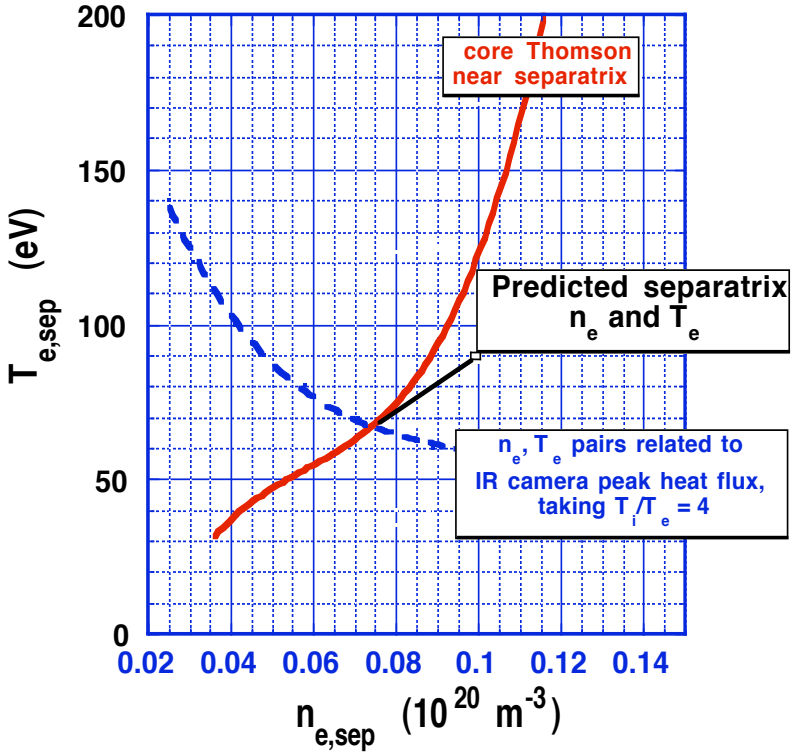




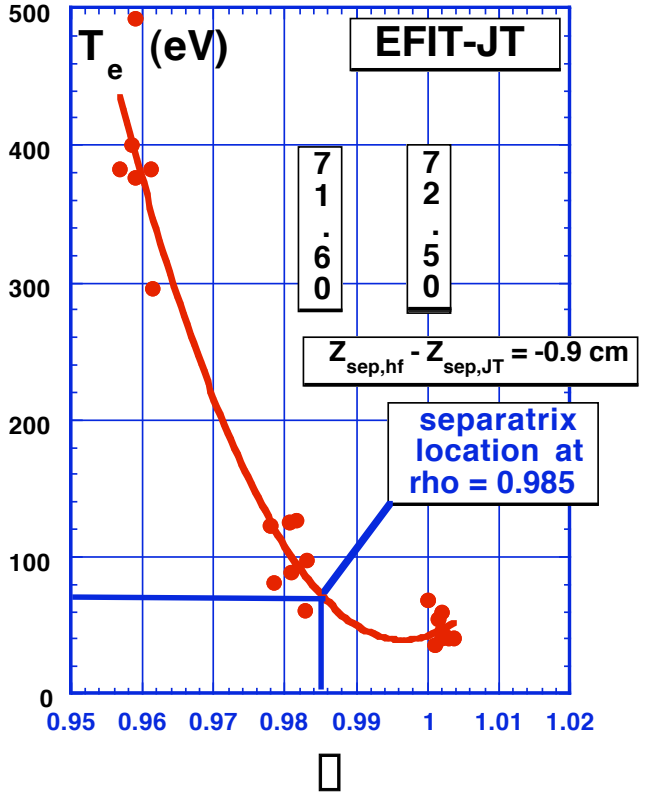
HEAT FLUX ANALYSIS RESULTS ARE CONSISTENT WITH A 1-2 cm DIFFERENCE SEEN BETWEEN EFIT AND THOMSON

- Using JT-like EFIT for mapping

UPSTREAM ELECTRON DENSITY AND TEMPERATURE ALONG THE SEPARATRIX MUST SIMULTANEOUSLY SATISFY BOTH THOMSON SCATTERING AND HEAT FLUX CONDITIONS



SHEATH-LIMITED ESTIMATE OF SEPARATRIX LOCATION IS SLIGHTLY AT VARAIANCE WITH EFIT-JT



THE EFFECTS OF ERROR FIELD ON MAGNETIC SURFACES ARE ESTIMATED USING A PERTURBATIVE APPROACH

- F-coil irregularities has recently been re-measured
  - F7A has largest ~ 1.2 cm radial shift as in previous measurements [1]
- Perturbative 3-D calculations
  - 3-D effects taken to be small, plasma assumed to remain in a 2-D axisymmetric equilibrium state
  - 3-D corrections to the magnetic surfaces are then computed by super-imposing the asymmetric external magnetic field onto the background toroidally symmetric magnetic field due to the plasma using a Green's function approach
  - PLOTLINE code

Radial Deviations of F-coil from B-coil (Luxon, Schaffer)

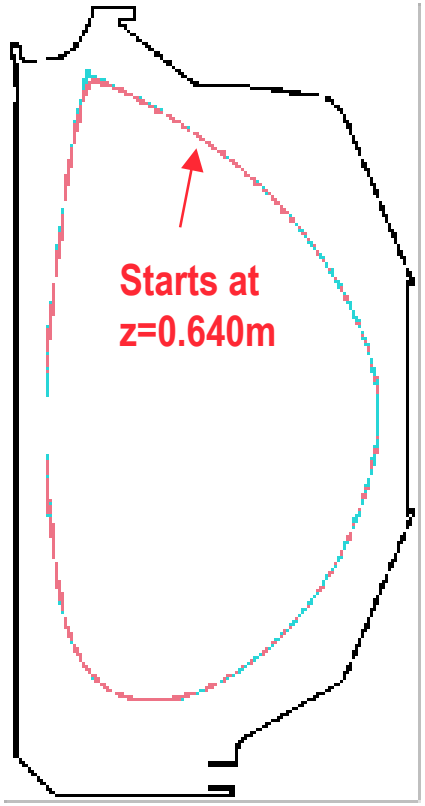
F-coil	Toroidal Angle	□r(cm)
F1A	24.237	0.210
F2A	-16.500	0.250
F3A	3.336	0.322
F4A	9.155	0.247
F5A	-37.307	0.271
F6A	-153.112	0.554
F7A	-101.527	1.206
F8A	-81.411	0.361
F9A	-95.623	0.310
F1B	-58.591	0.125
F2B	-43.359	0.295
F3B	-73.825	0.277
F4B	-72.300	0.185
F5B	-92.760	0.261
F6B	-108.792	0.692
F7B	-137.713	0.739
F8B	-163.708	0.604
F9B	-113.650	0.534

La Haye and Scoville, Rev. Sci. Instrum. 62 (1991) 2146

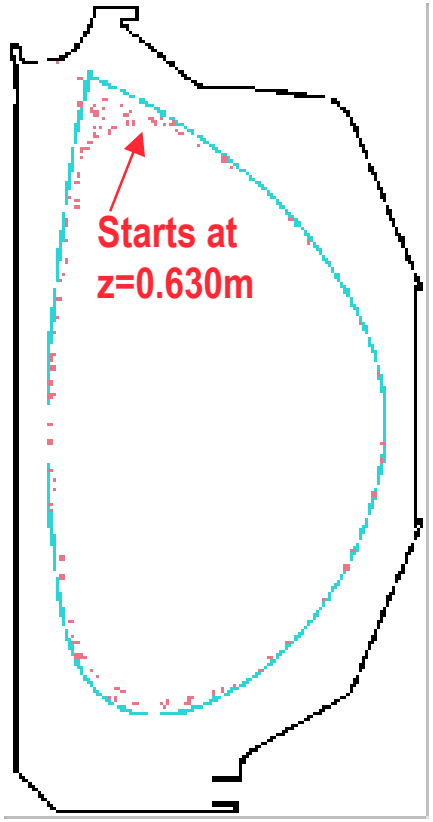
A 1-2 cm RADIAL SHIFT IN F-COILS CAN LEAD TO FORMATION OF A LARGE EDGE STOCHASTIC REGION

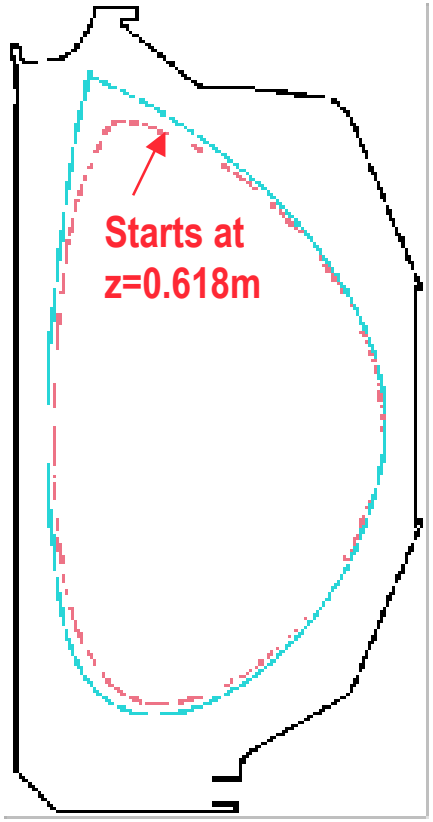
- 3-D perturbative calculations based on QH-mode USN discharge 105828 at 3000 ms

Axisymmetric



Shifted F-coils + C-coils



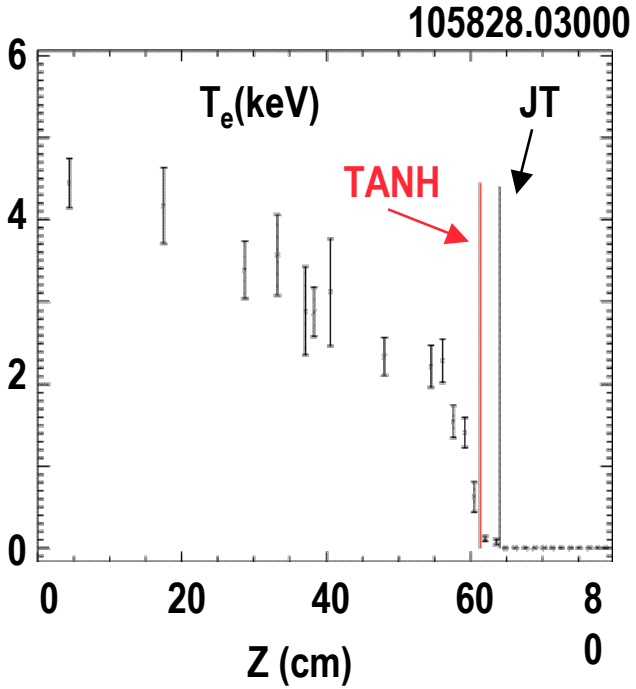


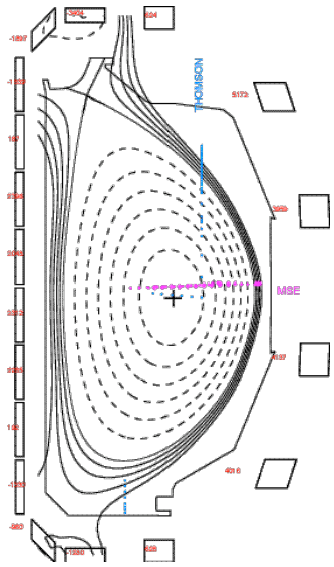
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

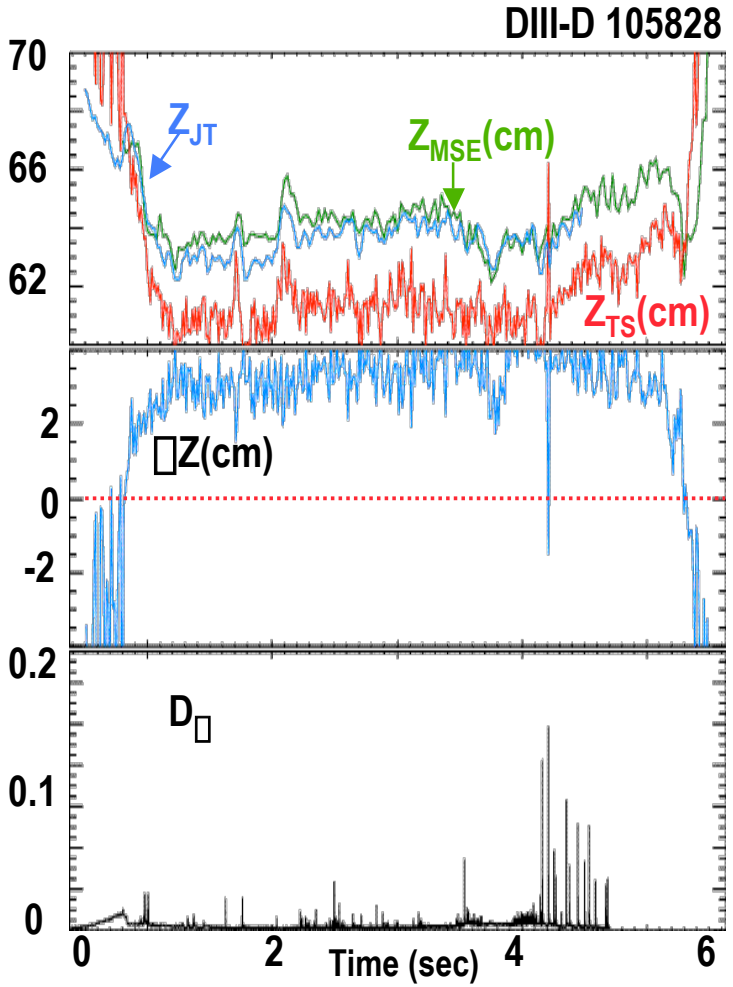
GENERAL ATOMICS

SEPARATRIX LOCATIONS FROM EFIT AND THOMSON DIFFER BY 2-4 cm IN THIS UPPER SINGLE-NULL DISCHARGE

- From 2001 QH mode experiment using 1.6 MA shape control panel

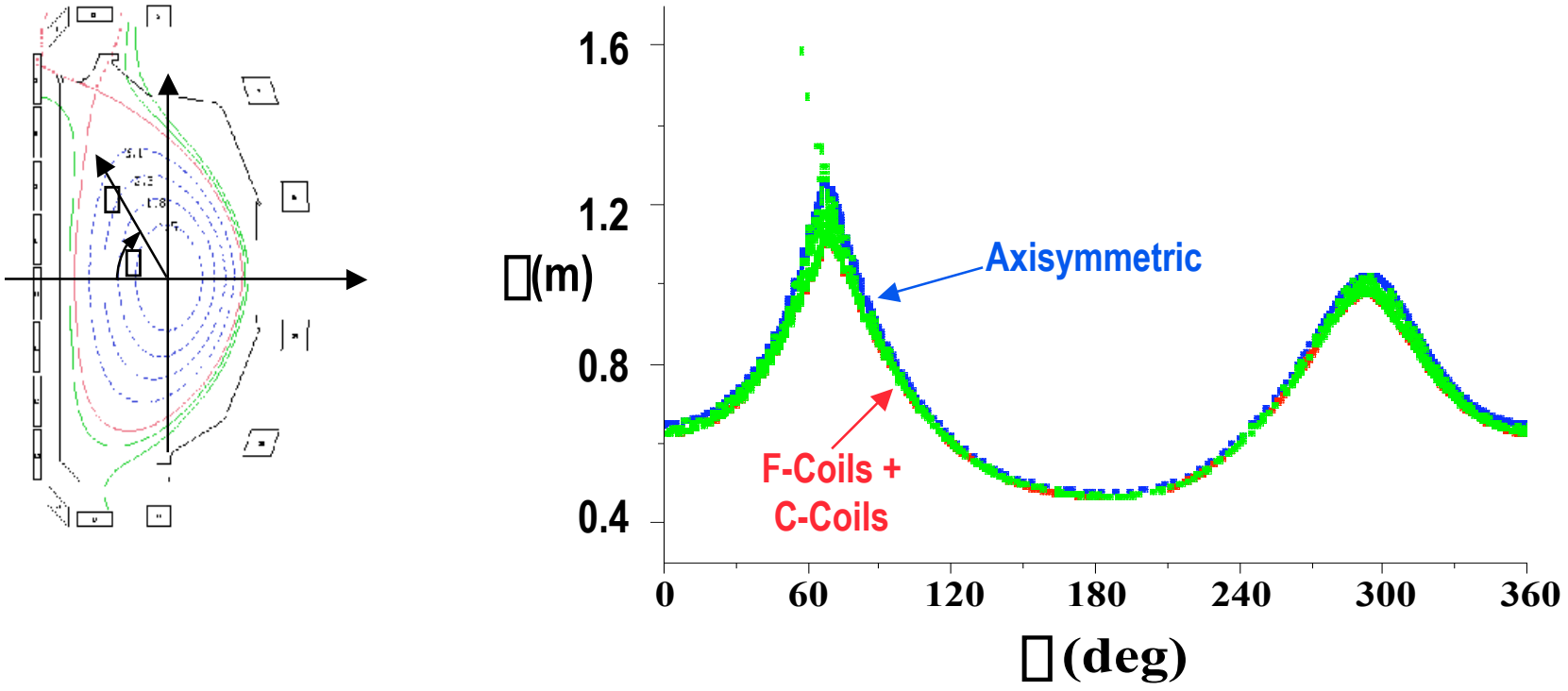






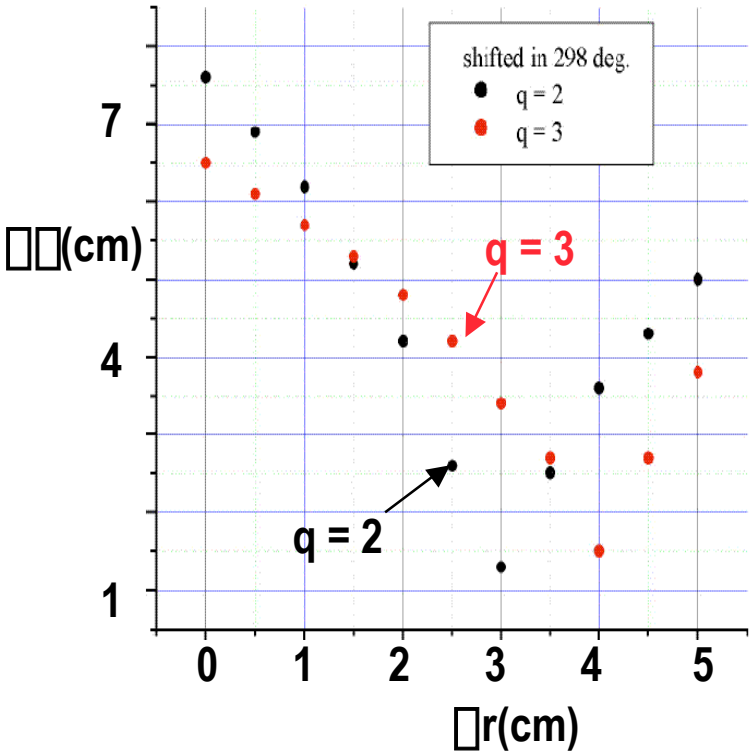
A SMALL TOROIDAL ASYMMETRY OF F-COIL LOCATION CAN PRODUCE A LARGE EDGE STOCHASTIC REGION

- DIII-D USN discharge 105828.03000

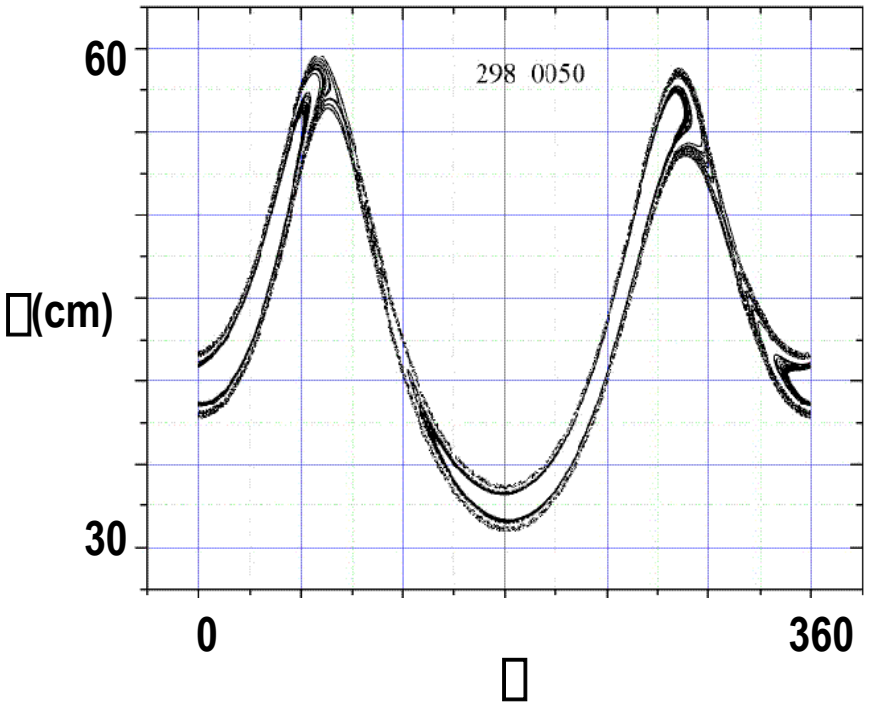


C-COIL CAN PRODUCE LARGE MAGNETIC ISLANDS AT OUTER RATIONAL q SURFACES WITHOUT PLASMA RESPONSE

- F-coil shifted uniformly along the radial direction at □ = 298 degree to reduce the C-coil effects at q = 2 and 3 surfaces
- Simulations based on DIII-D USN discharge 105828.03000

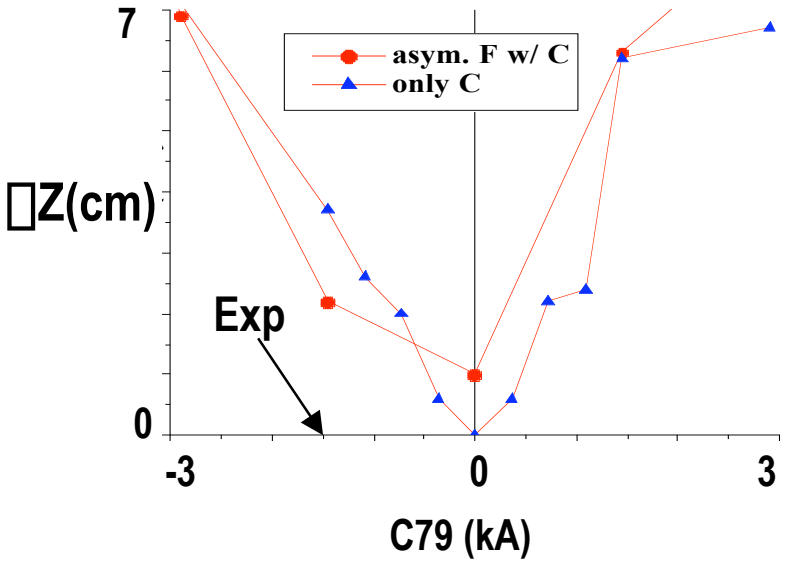


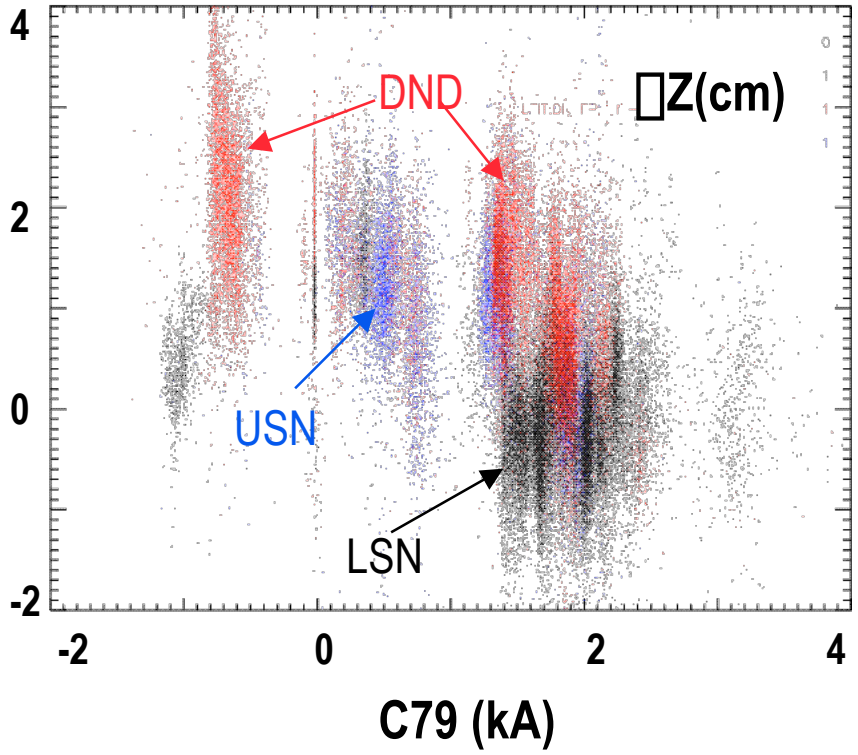
□r = 5 cm at □= 298 degree



C-COIL RESPONSES ARE NOT CONSISTENT WITH OBSERVATIONS WITHOUT PLASMA RESPONSE

- Main sorting variables: DND, USN, and LSN. H-mode only, 1999 - early 2001
- Simulations based on USN discharge 105828.03000 with asymmetric F-coils + C-coils and with C-coils only





STATUS OF 3-D EQUILIBRIUM / RECONSTRUCTION TOOLS TO MODEL PLASMA RESPONSE

- 3-D equilibrium
  - VMEC, restricted to nested flux surfaces
  - PIES, can model magnetic island and stochasticity but computationally intensive
  - Plasma response from linear stability code such as GATO and MARS
    - V3RFUN + V3POST [1]
- 3-D reconstruction tools in development
  - V3FIT, stellarator reconstruction project based on the efficient EFIT response function approach + VMEC (ORNL. GA, Auburn University) RP1 27
  - Complementary integral approach
    - Filamental plasma response MFIT3D (GA, PPPL)
    - Full plasma response EFIT3D

[1] Hirshman, Lazarus, Hanson, Knowlton, Lao to appear in Physics Plamsa

SUMMARY / PLAN

- A 1 - 4 cm difference still exists between the separatrix vertical position determined from EFIT magnetic analysis and those inferred from Thomson T_e measurements
  - Removal of metal plate on n1-coil makes little difference
- Perturbative calculations without plasma response indicate a small toroidal asymmetry in the external coil location can introduce significant 3-D magnetic effects such as formation of edge stochastic layers and magnetic islands into the magnetic topology
- Response of error magnetic field correction coils (C-Coils) suggest that plasma response may play a crucial role
  - C-coil currents tend to increase the error magnetic field due to the external shaping coils
- Plan
  - New magnetic uncertainty matrix
  - 3-D equilibrium analyses / development
    - VMEC / PIES analyses
    - GATO / MARS + V3RFUN + V3POST
    - MFIT3D, EFIT3D