# Current-driven discharges in the Compact Toroidal Hybrid (CTH) experiment

S. Knowlton, G. Hartwell, J. Hanson, J. Peterson, B. Stevenson

*Auburn University, Auburn, Alabama*

OUTLINE:

- Overview of the CTH experiment
- Validation of vacuum configuration; correction of magnetic field errors
- Initial studies of behavior associated with plasma current

Joint 17th International Toki Conference (ITC) on Physics of Flows and Turbulence in Plasmas and 16th International Stellarator/Heliotron Workshop (ISHW) 2007

# Research areas of CTH experiment

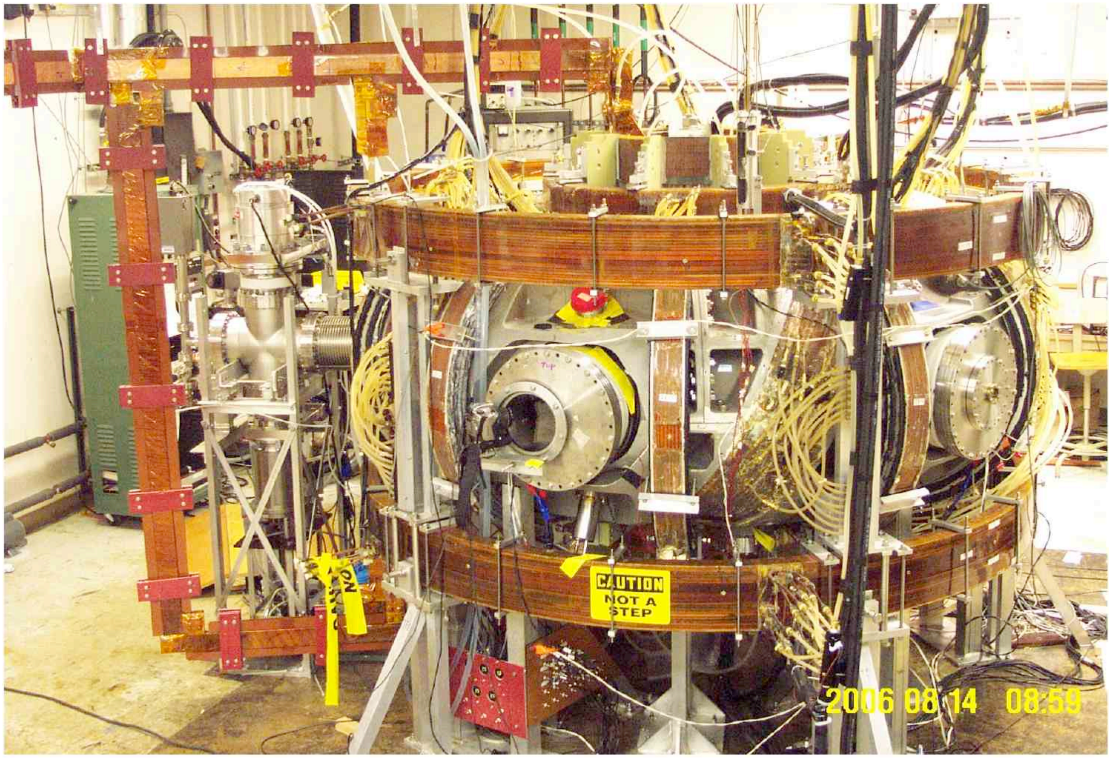
- **Current-driven instabilities/ avoidance of disruptions in stellarators**
  - NCSX and, to lesser extent, QPS, will rely on bootstrap current to provide rotational transform for optimization of configuration
  - Bootstrap current influences high-$\beta$ stellarator equilibria in present experiments
  - previous results from JIPPT-2, W7-A, W7-AS with large fraction of ohmic transform in low shear stellarators

- **Determination of experimental magnetic equilibrium in 3-D plasma**
  - Test V3FIT 3-D equilibrium reconstruction with diagnostic data

    => status of V3FIT; poster by Hanson et al., this workshop

- **Role of magnetic islands in highly variable transform profiles**
  - Minimize resonant field errors at rational surfaces by design and active correction

# CTH: *l* / M = 2 / 5 torsatron




5 field periods; circular Inconel vacuum vessel

$R_o$ = 0.75 m, R/<a> ≥ 4
$B_o$ ≤ 0.7 T
$I_p$ ≤ 40 kA; Δι ≤0.5

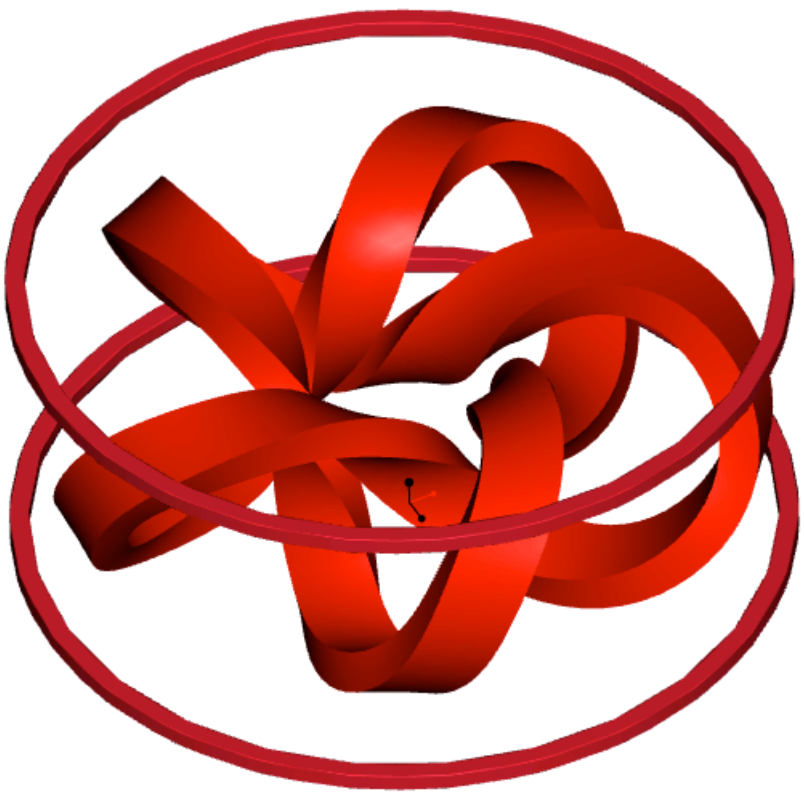
$P_{in}$= 12 kW ECRH @18GHz
$B_0$ => 0.64 T (1st harmonic)
60 kW OH

Vacuum ι(a): 0.05 – 0.6

Discharge duration: 0.5 s
w/ OH: 0.1 s

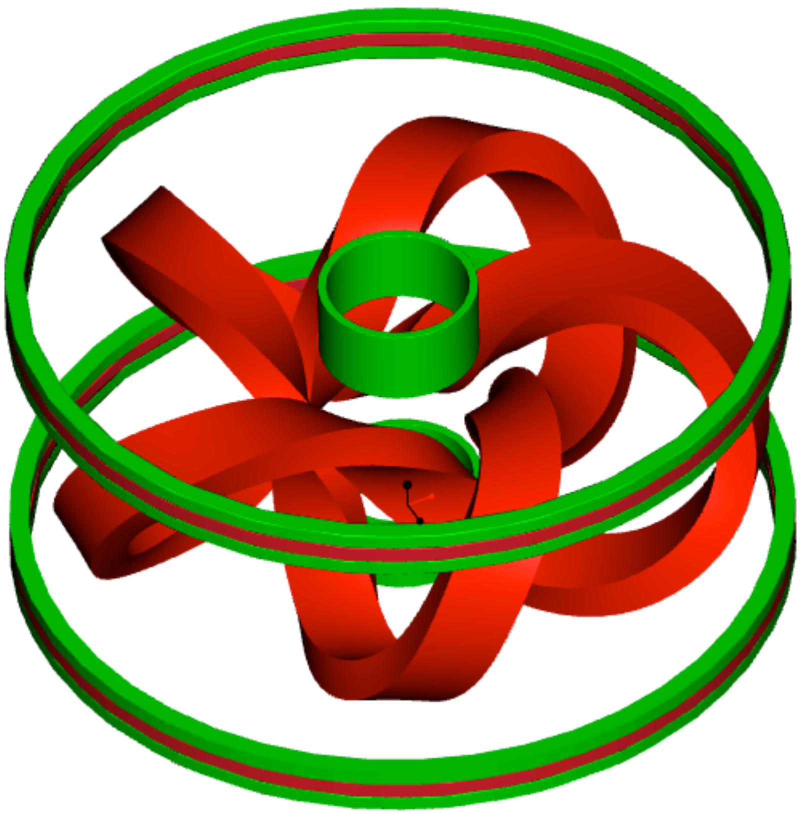
$\langle n_e \rangle = 0.2 - 1 \times 10^{19}\ m^{-3}$
Single-channel, radial path interferometer

# CTH configuration designed for flexibility

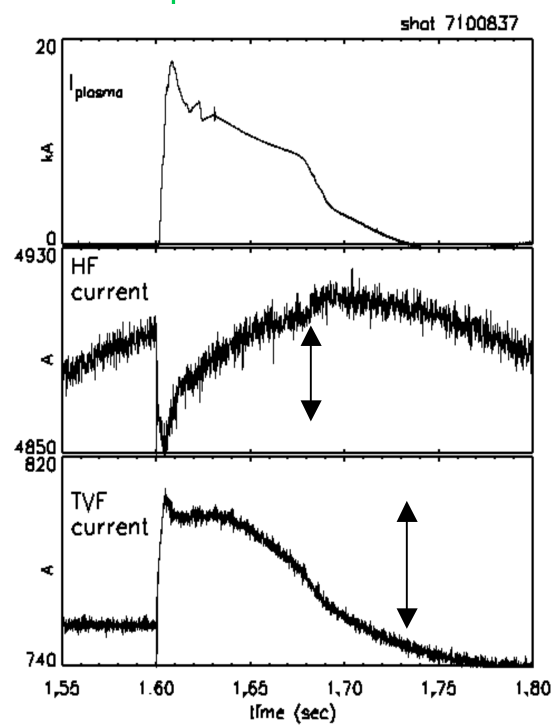


- Main vertical field coil in series with $l$ / M = 2/5 HF field winding
- Torsatron HF coil decoupled from ohmic flux with external decoupler

# CTH configuration designed for flexibility



- Trim vertical field with ohmic decoupler
  - Decoupler overcompensates ohmic flux to provide programmed vertical field for equilibrium with plasma current

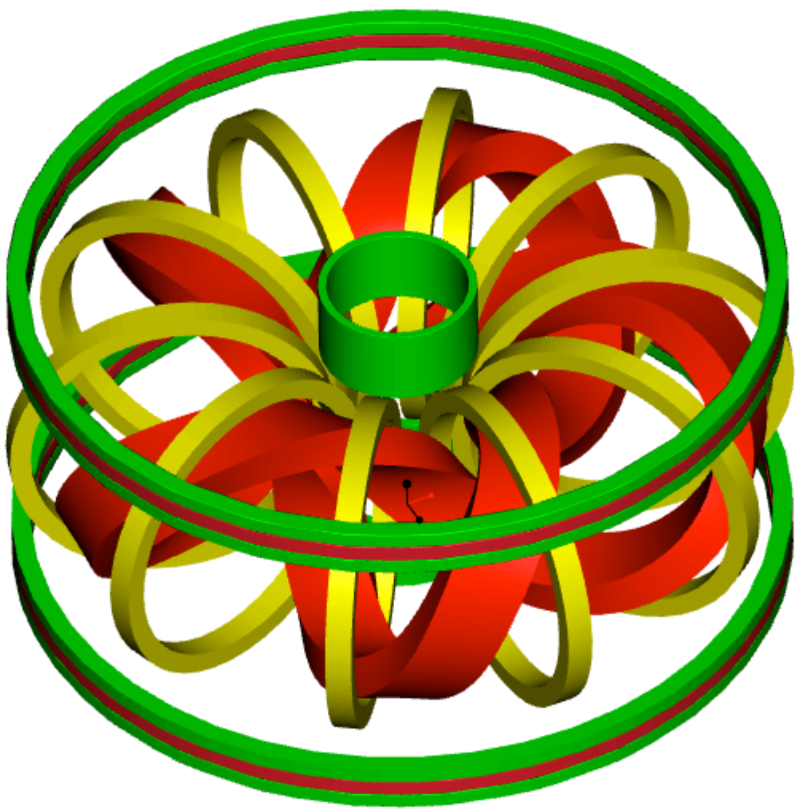



$\Delta I_{HF}/I_{HF} < 1\%$

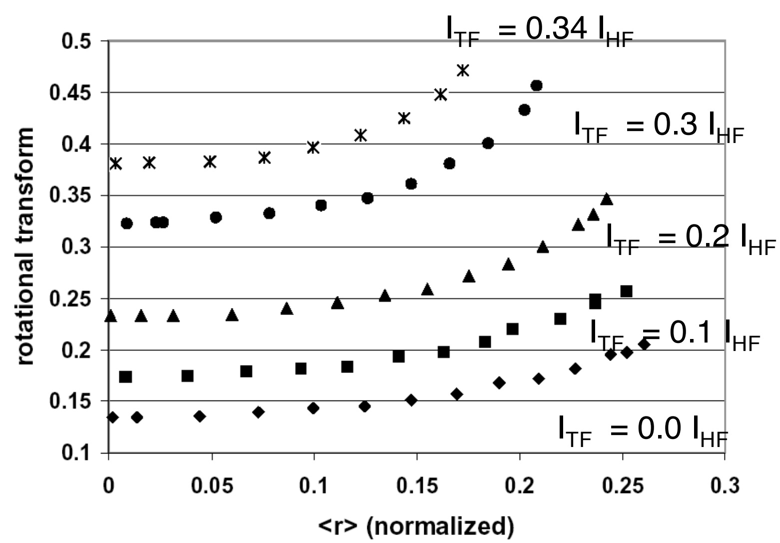
$\Delta I_{TVF}/I_{TVF} \sim 10\%$

=> $\Delta R \leq 1$ cm during OH pulse

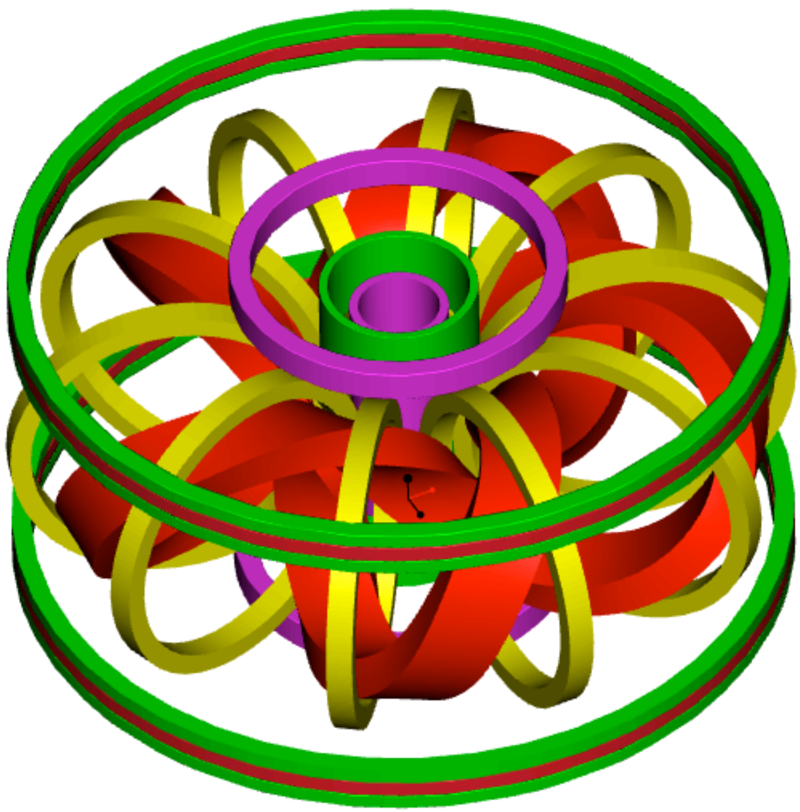
# CTH configuration designed for flexibility



- Main vertical field coil in series with *l* / M = 2/5 HF field winding
- Trim vertical field with ohmic decoupler
- Toroidal field coils for variation of rotational transform



# CTH configuration designed for flexibility

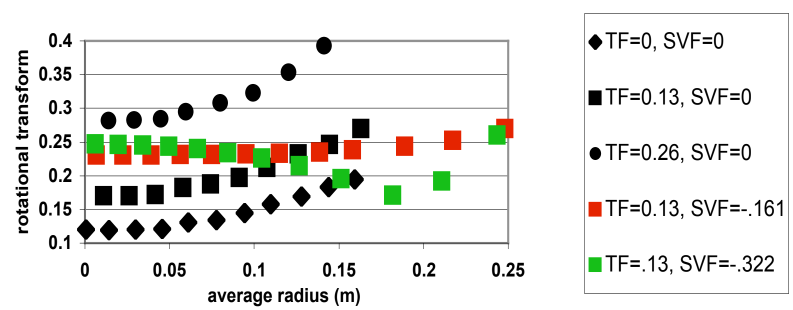


Main vertical field coil in series with $l$ / M = 2/5 HF field winding

Trim vertical field with ohmic decoupler

Toroidal field coils for variation of rotational transform

Shaping (quadrupole) coils for shear variation; also has ohmic decoupler



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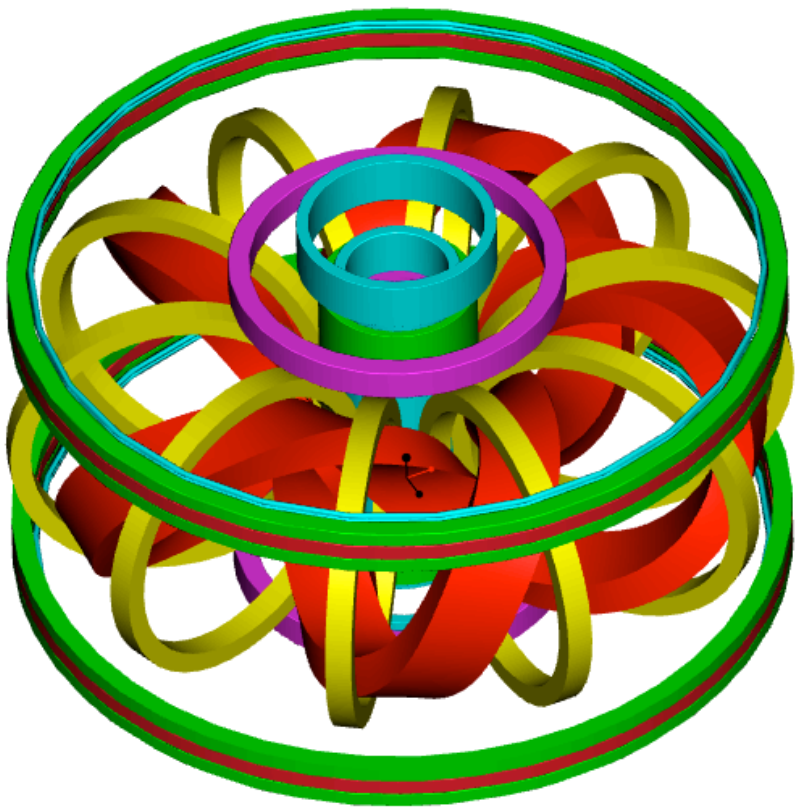


Main vertical field coil in series with *l* / M = 2/5 HF field winding

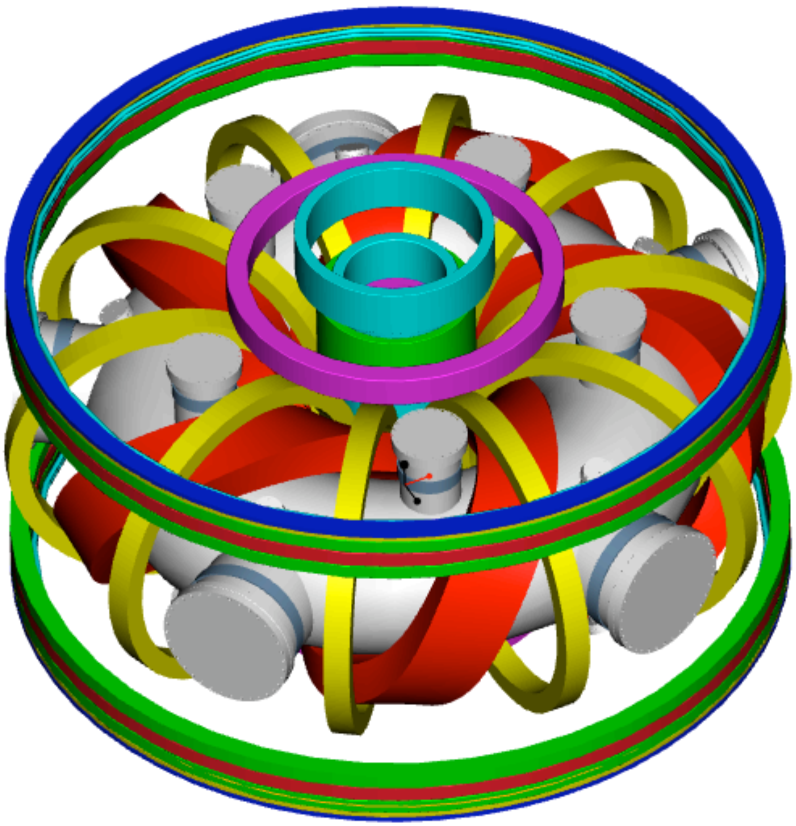
Trim vertical field with ohmic decoupler

Toroidal field coils for variation of rotational transform

Shaping (quadrupole) coils for shear variation; also with ohmic decoupler

Ohmic coil stack powered by capacitor banks

# CTH configuration designed for flexibility



Circular vacuum vessel

Main vertical field coil in series with $l$ / M = 2/5 HF field winding

Trim vertical field with ohmic decoupler

Toroidal field coils for variation of rotational transform

Shaping (quadrupole) coils for shear variation; also with ohmic decoupler

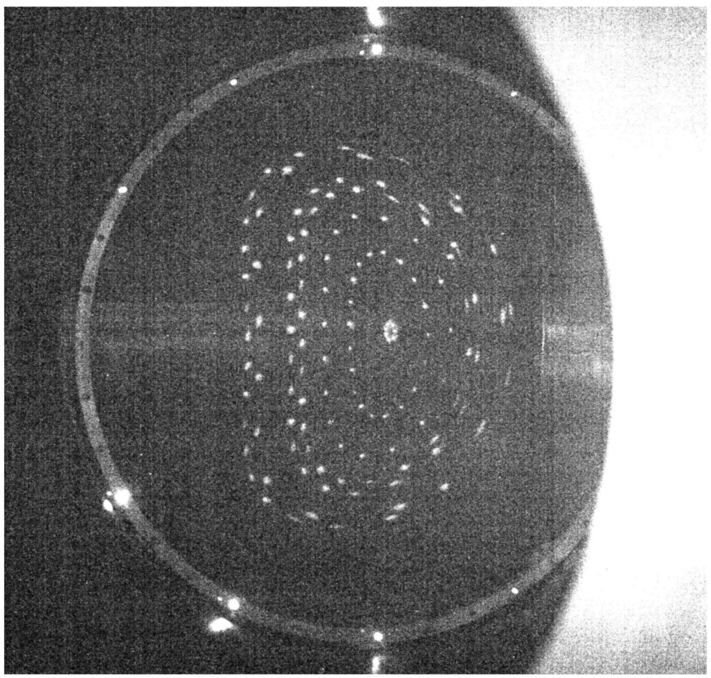
Ohmic coil stack powered by capacitor banks

15 Error correction coils mounted on ports

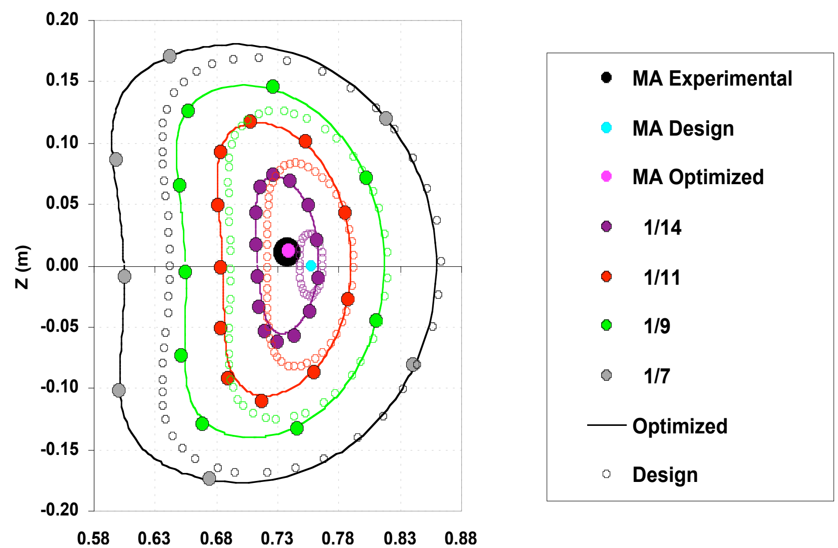
Additional PF coils for vertical positioning if necessary

# CTH exhibits good vacuum flux surfaces

Low aspect ratio configuration achieved at rotational transform ($\iota_{edge} \leq 0.2$)

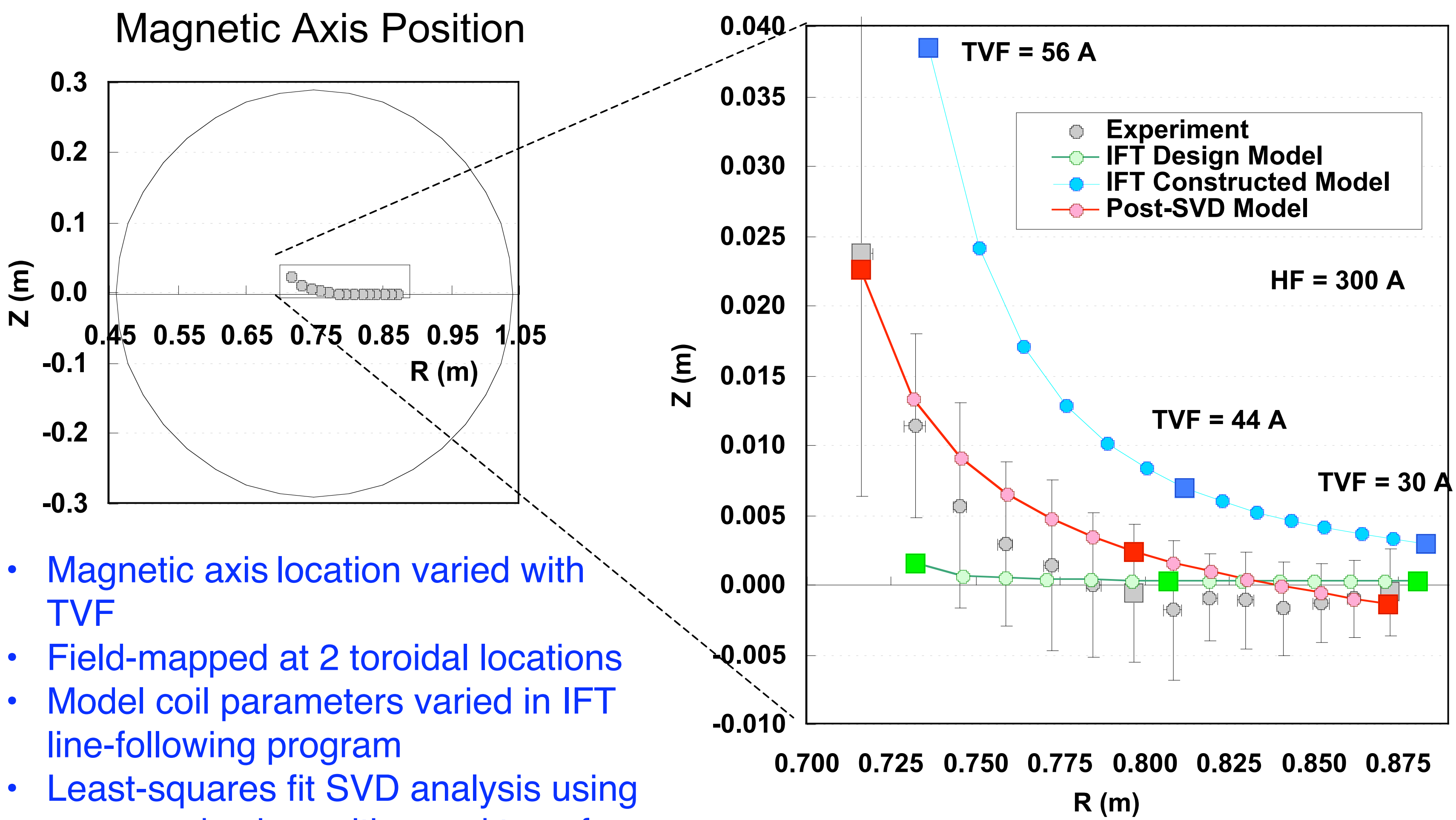


Composite photo of measured flux surfaces




Comparison with of original coil model with experiment.

# Field-mapping of magnetic axis applied to correction of coil positions




- Magnetic axis location varied with TVF
- Field-mapped at 2 toroidal locations
- Model coil parameters varied in IFT line-following program
- Least-squares fit SVD analysis using measured axis position and transform

# Required corrections to coil model are minor

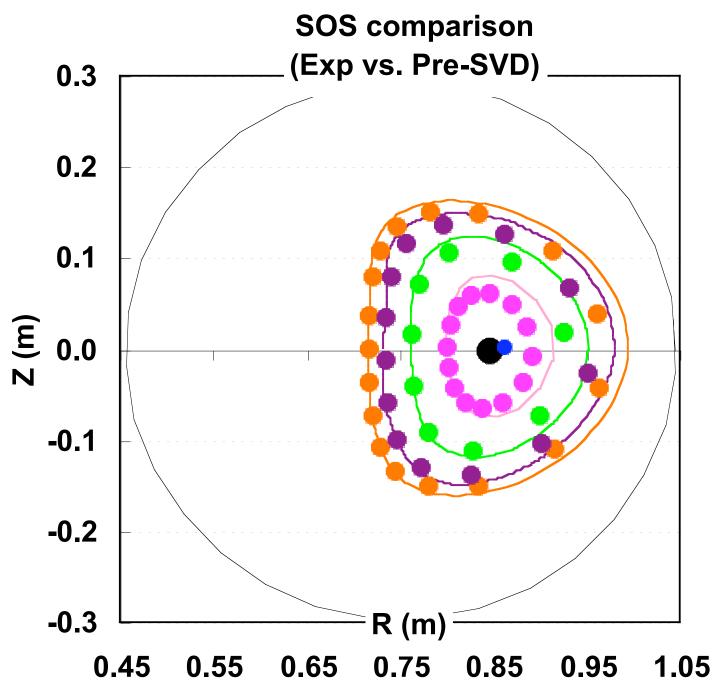
Optimization of HF/VF coils includes $B_{EXT}$, poloidal coil positions and radii, helical coil winding law

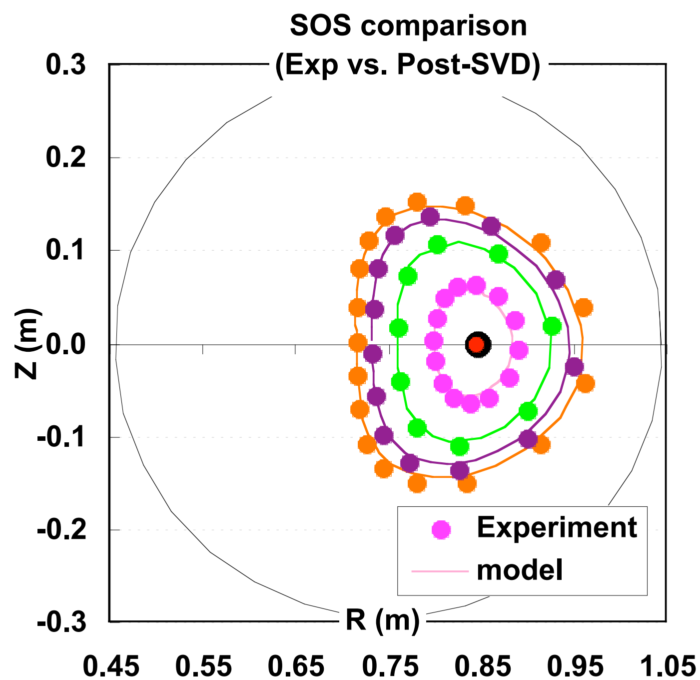
Helical coil winding law

$$\phi = 2/5\,\theta + \alpha_1 \cos\theta + \beta_1 \sin\theta + \alpha_2 \cos 2\theta + \beta_2 \sin 2\theta + \ldots$$

$$r_{COIL} = r_0 + a_1 \cos\theta + b_1 \sin\theta + \ldots$$

| | $r_0$(m) | $a_1$(m) | $b_1$(m) | $\alpha_1$ | $\beta_1$ | $\alpha_2$ | $\beta_2$ |
|---|---|---|---|---|---|---|---|
| Design: | 0.385 | 0 | 0 | 0 | –0.2520 | 0 | 0.0520 |
| After analysis: | 0.3826 | 0.0012 | -0.001 | 0.0005 | –0.2522 | 0.0 | 0.0530 |

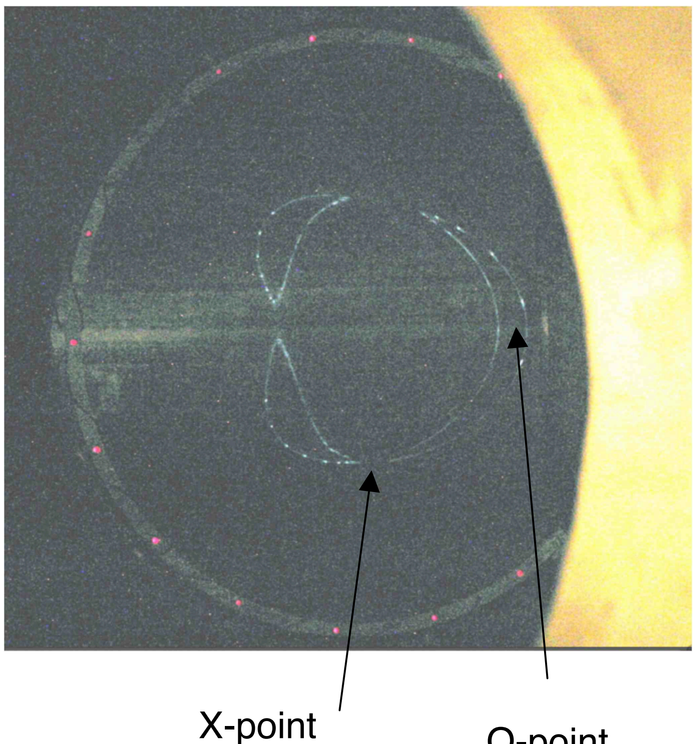


# Magnetic islands on rational surfaces

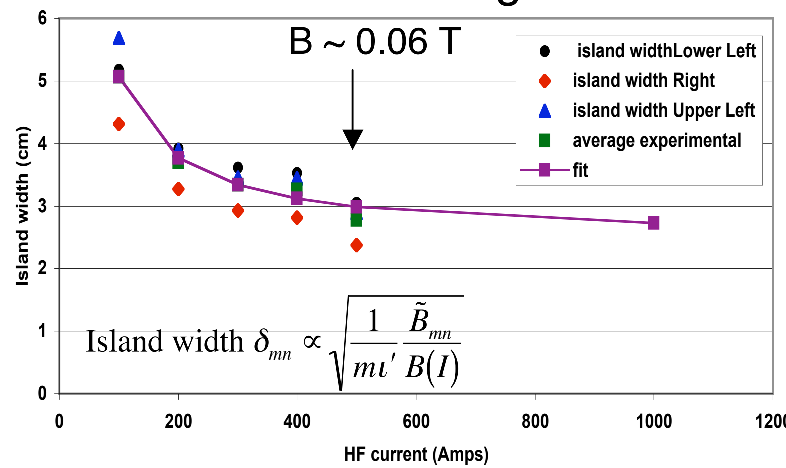
With auxiliary TF coils,vacuum rotational transform can be raised to $\iota(a) \leq 0.6$

$\iota$= 1/3, 2/5, 1/2 rational surfaces exhibit islands at low fields for field mapping.




n/m = 1/3 static magnetic island

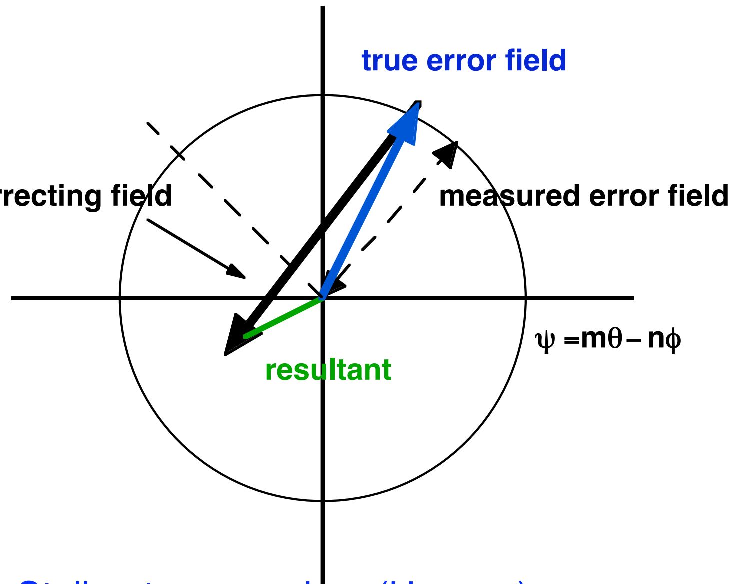
Island width vs magnetic field




Island size decreases with increasing field

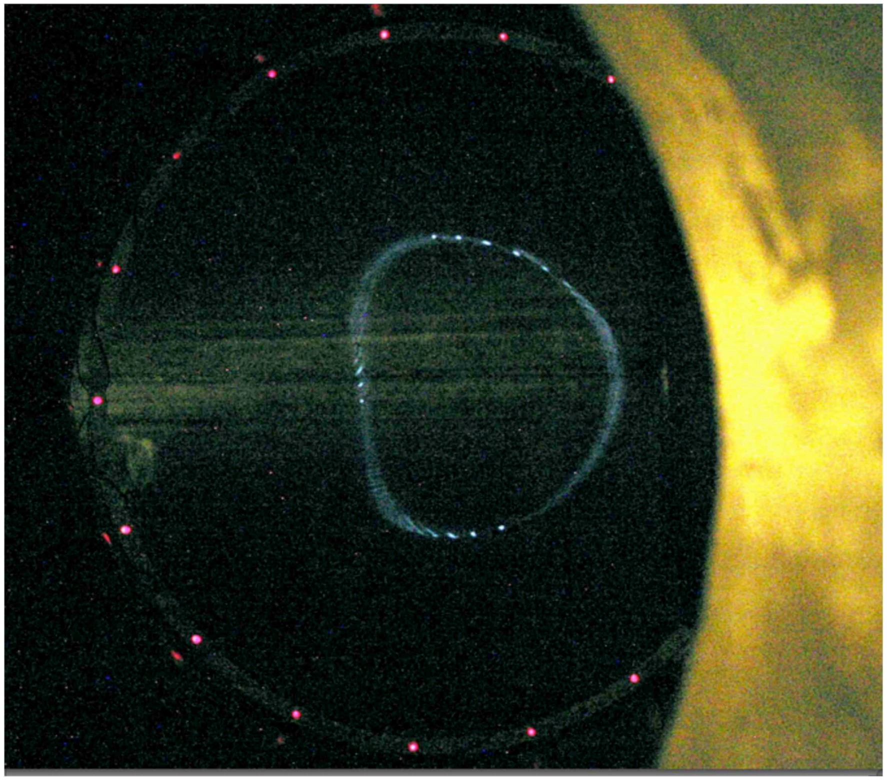
- Observed islands at low mapping currents only partly due to winding errors
- Projects to island width ≤ 2 cm at operating currents of 5 kA (B= 0.5 - 0.7 T)

# Island reduced by application of primary & secondary corrections



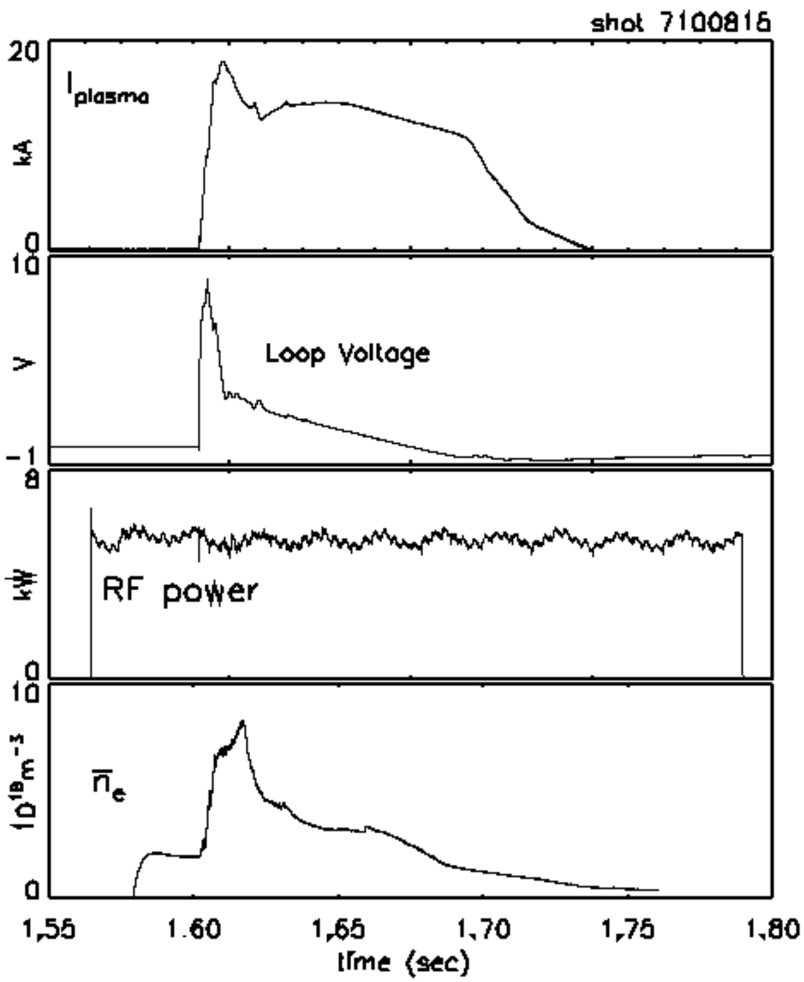

Fix Stellarator procedure (Hanson)

- Determine phase of island O or X-points
  $\psi = (m\theta_f - n\phi_f)$ in flux coordinates.
- Compute correction field of opposite phase; generate vector of N elements
  N = no. of independent correction coils
- Complete minimization by applying additional correction orthogonal to original vector.



n = 1 correction applied with 5 coils

# Ohmic currents induced in ECRH target plasmas

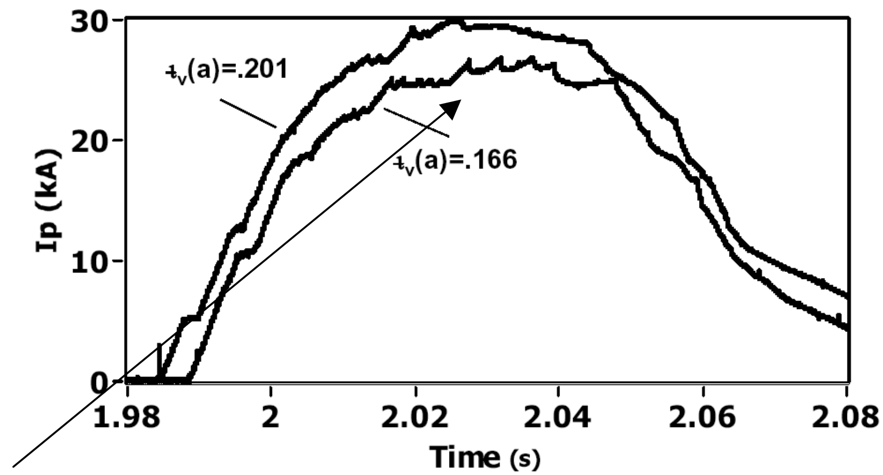



- Ohmic heating pulse applied to ECRH plasmas at fundamental resonant field of $B_0$ = 0.64 T.
- Density increases with ohmic current
- Discharges with $\iota_{tot}(a)$ > 0.7 obtained with $i_{VAC}(a)$ ~ 0.2

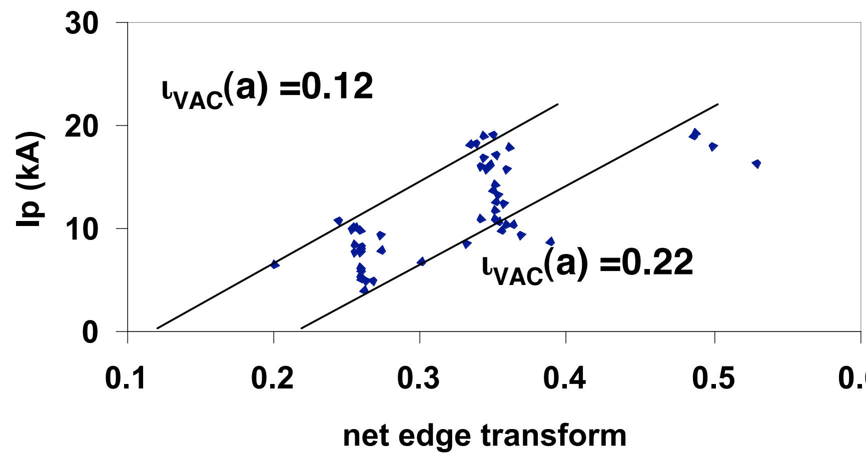
# Current-driven plasmas show hesitations during current rise

- Hesitations occur at/near rational values of edge transform.
  - Vacuum rotational transform varied with auxiliary toroidal field coils.
- Some unstable behavior observed during main phase of ohmic discharge
  - Current relaxations with bursty precursor MHD oscillations often occur
  - May be associated with internal n/m = 1/3, 1/2 islands, possible non-monotonic transform profiles
    - address in future with shaping of vacuum shear.
  - Despite unstable behavior, no complete current collapse observed

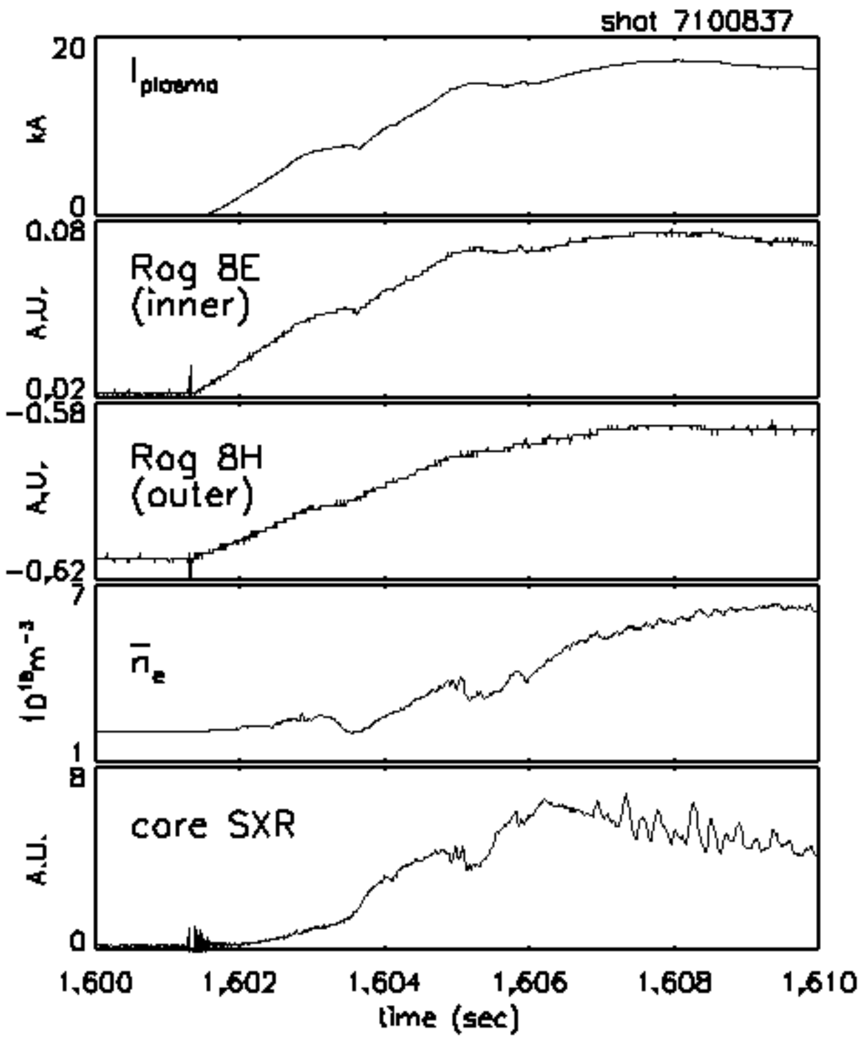
Plasma current for 2 different vacuum transforms




Data represent plasma current values at hesitations



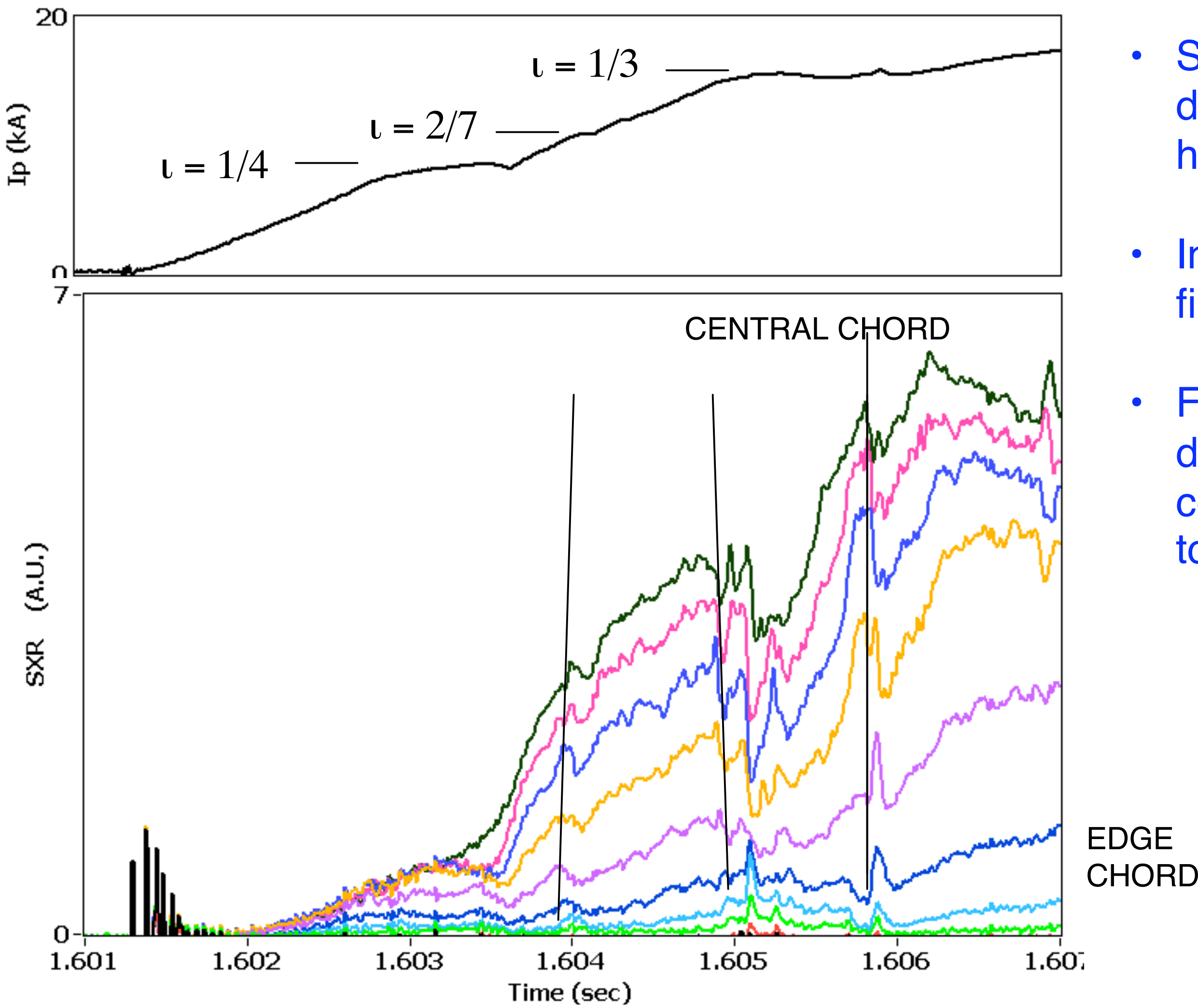
# Current-rise hesitations observed on magnetic and other diagnostics



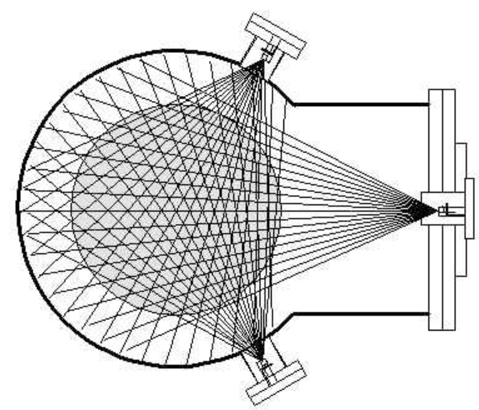

- 8-segment poloidal Rogowski coil shows slight outward shift of current centroid during hesitation, suggesting narrowing of current profile when rational surface in contact with edge.
  - V3FIT used in predictive mode to model magnetic diagnostic responses from VMEC equilibrium; from relative measurements estimate outward shift of 5 mm during hesitation
  - Further calibration work of diagnostics required for reconstruction
- In contrast to later part of discharge, no bursty MHD activity observed during current rise hesitations
- Decreases in line-averaged density and core SXR emission during hesitations

For progress on V3FIT reconstruction, see poster by Hanson et al, Wednesday afternoon

# Horizontally-viewing SXR profile during current rise




- Soft X-ray profiles typically decrease during current hesitations.
- In early hesitations, decrease first evident in edge chords
- For later hesitations, decrease first evident in central chord and propagates to edge in ~ 80 μs



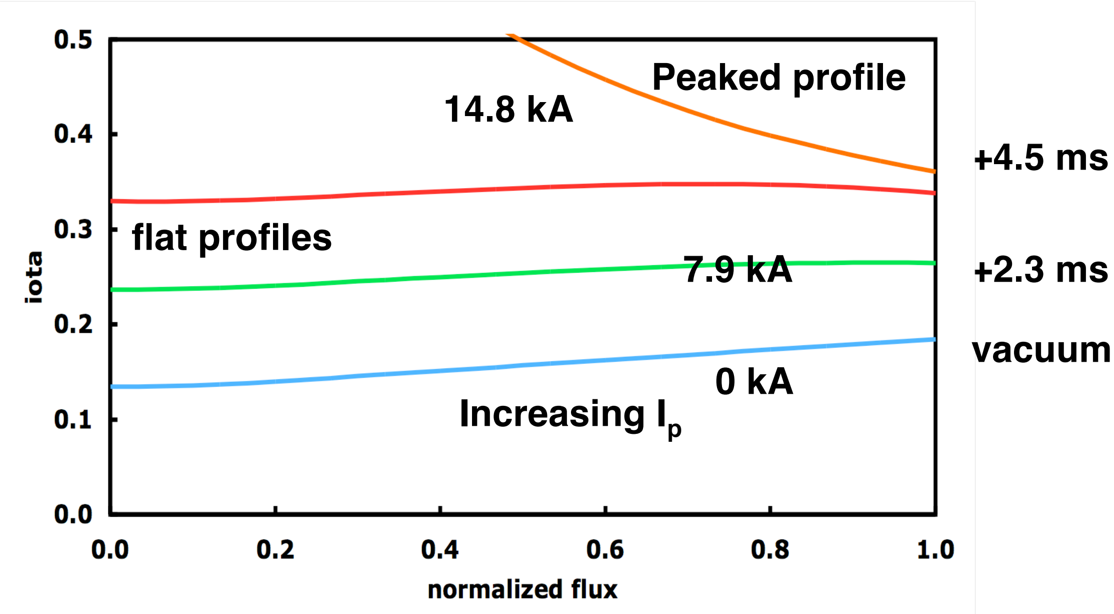
# Discussion

- Expect profiles to evolve from positive (stellarator) shear through double-valued to negative as ohmic current profile peaks on resistive time scale.
  4 msec time scale consistent with assumed $\langle T_e \rangle \sim 100$ eV, $Z_{eff} \sim 2$

- Early behavior (t< 4 ms) consistent with positive shear profiles

- Hypothesis: island at edge rational surface causing narrowing of current channel, density drop. Recovery occurs as rational surface moves inward

Model transform profiles during current-rise

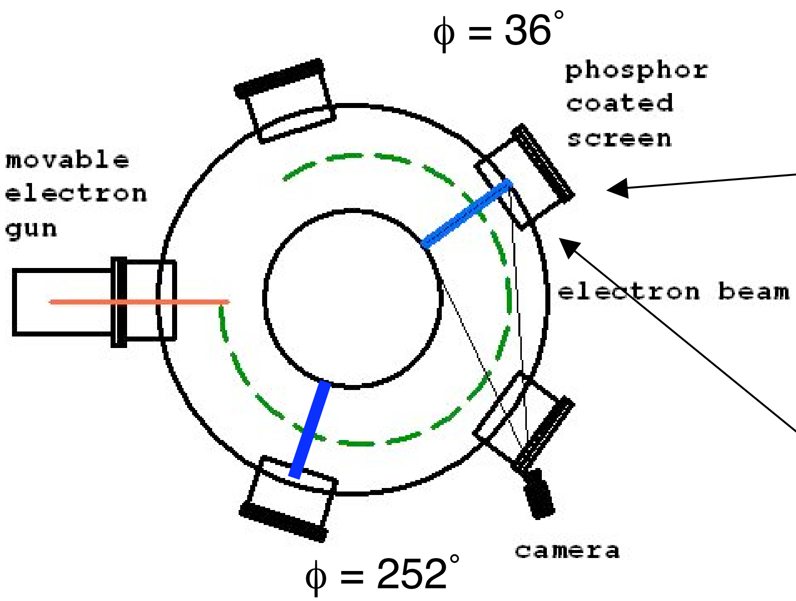


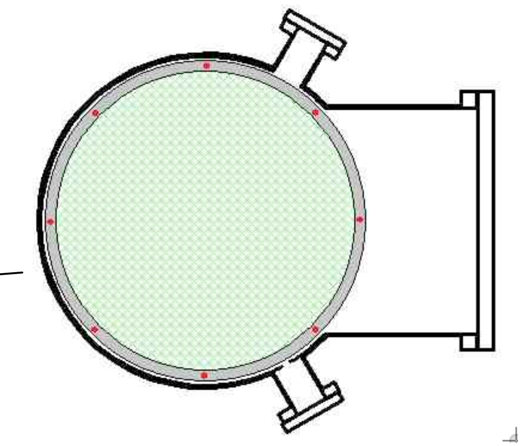

Presently testing applying n = 1 perturbation with error correction coils to determine effect of variable static island on current-rise behavior

# Concluding remarks

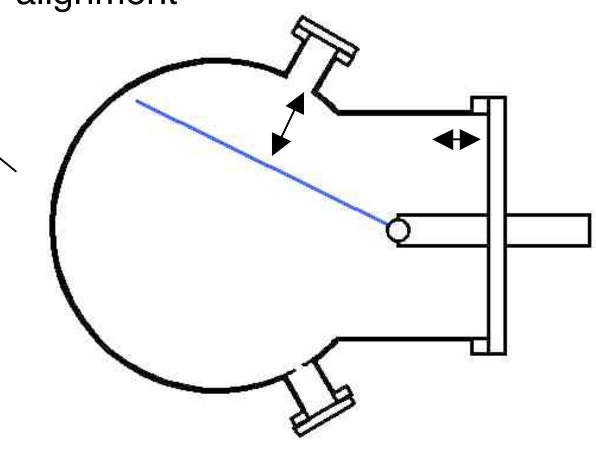
- Field-mapping results used to adjust model of equilibrium coils
  - SVD fitting procedure indicates deviations of up to 1.5 mm in helical coil radius, 1 mm-scale deviations in other winding law parameters, and external fields of ≤ 2 gauss.
  - Similar procedures performed on other coil sets
- Low order islands observed in vacuum configuration corrected
  - Experiments applying static n = 1 perturbation of variable amplitude to plasma discharges are underway.
- Hesitations in current-rise and density decreases associated with rational values of edge transform.
  - Otherwise, current-rise plasmas are stable while transform profile remains monotonic.
  - -will vary vacuum shear in further studies.

# Field-mapping set-up on CTH



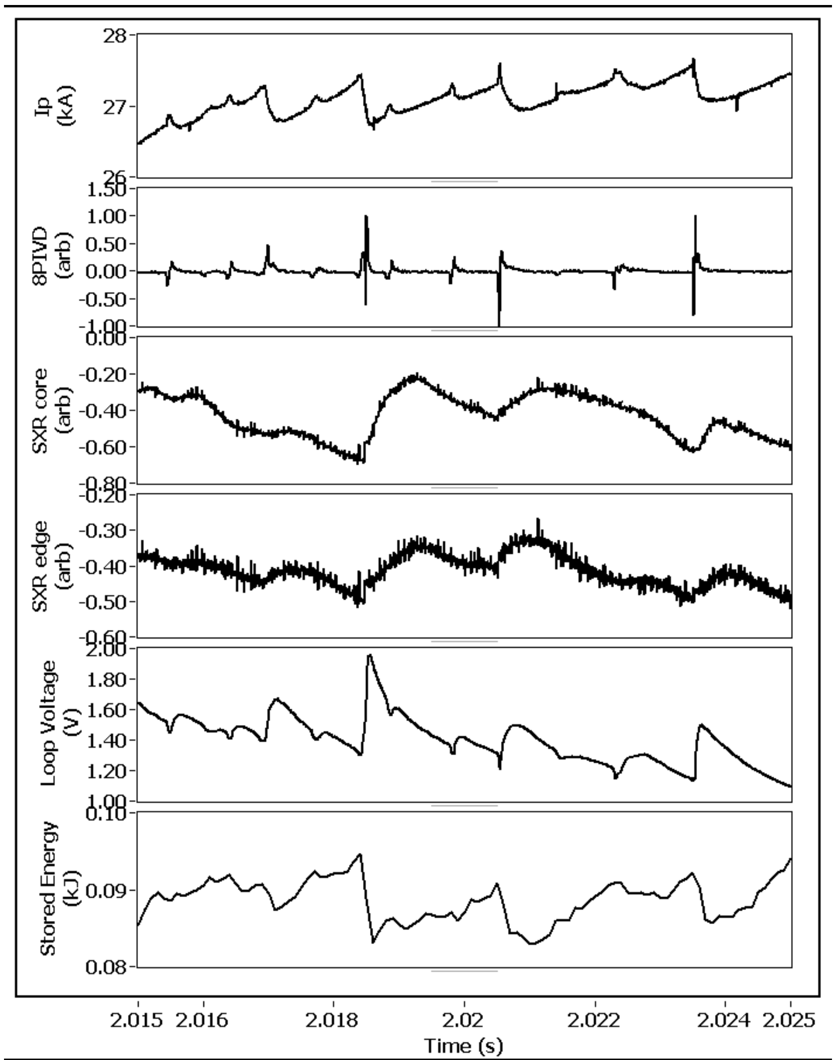
ZnO phosphor-coated wire mesh w/ LED's at edge for alignment



Movable phosphor-coated wand

Entire set-up (gun, screen, camera) rotated toroidally by two field periods to test for n=1 shifts in equilibrium.

# Unstable behavior following current rise




- Plasma current shows relaxation-type behavior
- Bursty MHD oscillations on partial Rogowski loops
- Soft X-ray emission increases after relaxation
  - Runaway generation
- Disruptive spikes on loop voltage
- Drop in stored energy following relaxation