Disruption control using external transform in low-β plasmas in the Compact Toroidal Hybrid (CTH)

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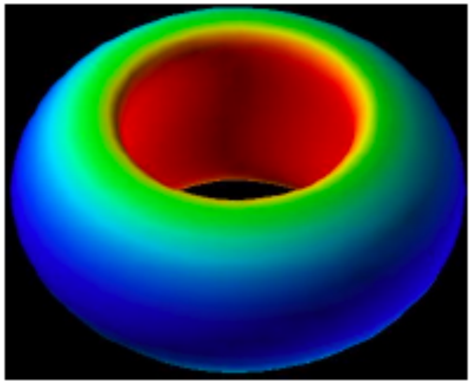
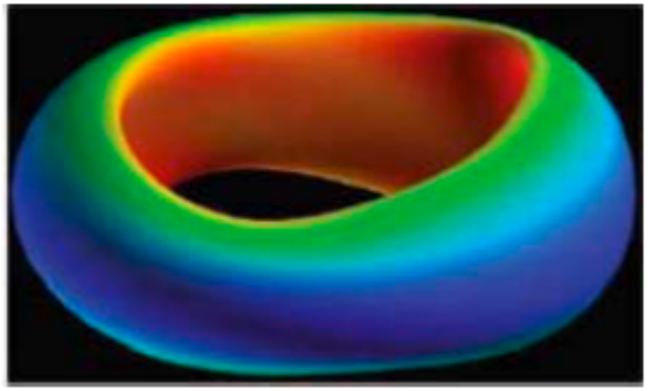
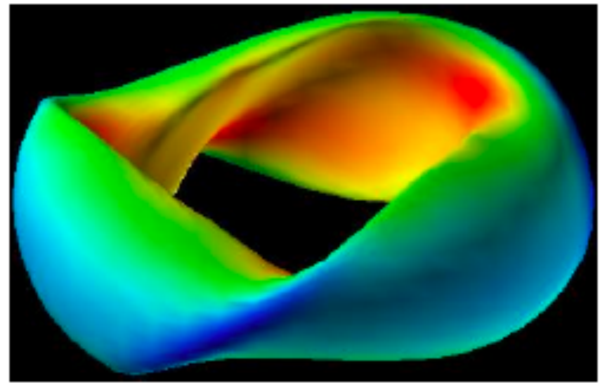
CTH

Compact Toroidal Hybrid

Can addition of 3D equilibria to tokamak permit passive avoidance of disruptions?







Tokamak $\iota_{VAC} = 0$

$\iota_{VAC} / \iota_{TOT} = 20\%$

High-β stellarator

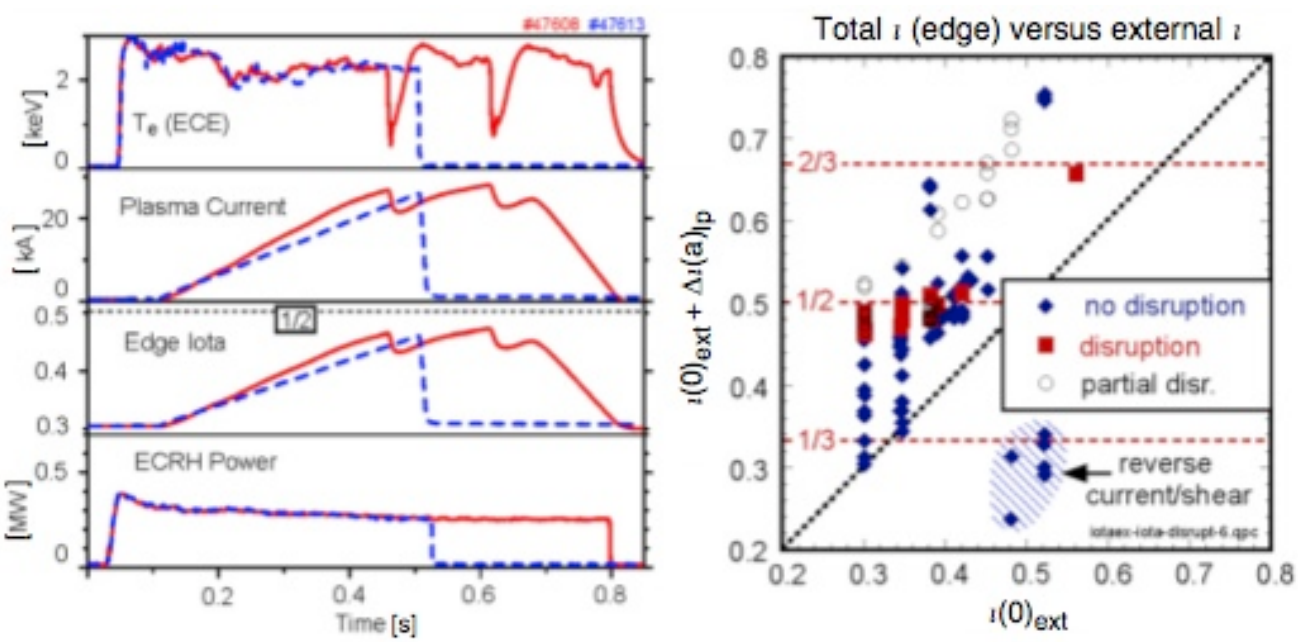
$\iota_{VAC} / \iota_{TOT} = 75\%$

A. Boozer, 2008

- **Net rotational transform** ι_{TOT} from both plasma current $\iota_{CURRENT}$ and external stellarator coils ι_{VAC}.
  Reduces need for plasma current.
- What level/profile of "stellarator" rotational transform suffices to gain passive control of
  - VDEs
  - Density-limit disruptions
  - Low-q disruptions

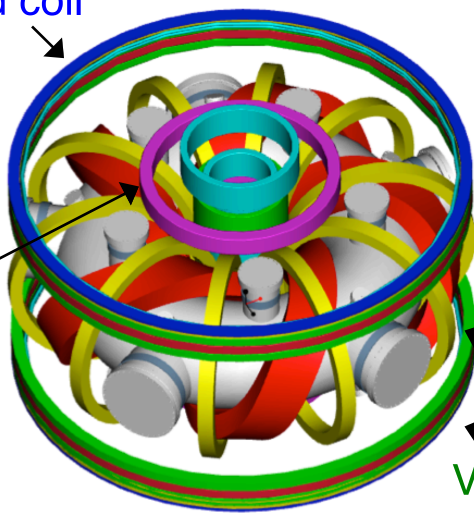
Earlier hybrid stellarator experiments found evidence of disruption avoidance

- W7-A and later JIPPT-2 found $\iota_{VAC} \geq 0.14$ sufficient to avoid disruption in low-shear stellarator plasmas with ohmic current (1979).
  - Decoupling of ι-profile from current profile to avoid destabilizing of tearing modes
  - Higher "thresholds" of vacuum transform required to avoid disruption in ECH/NBI heated plasmas on W7-A, W7-AS.



W7-AS (2000)

CTH tests MHD stability of current-carrying stellarator plasmas



Stellarator plasma generated by ECRH

- target for ohmic current drive

5 field periods

$R_o = 0.75$ m

$\langle a \rangle \leq 0.25$ m

$B_o \leq 0.7$ T

$\iota_{VAC}(a)$: 0.03 – 0.32

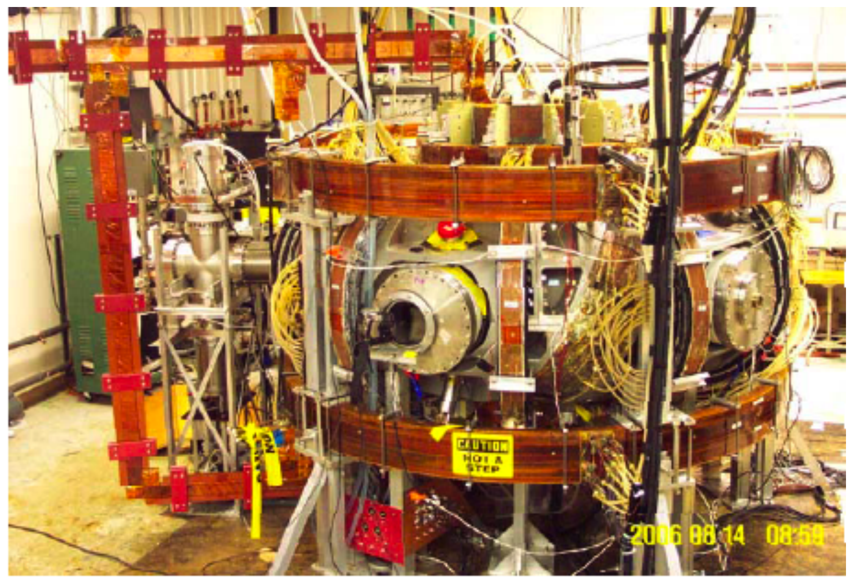
$I_p \leq 60$ kA; $\Delta\iota \leq 0.6$

$\langle n_e \rangle = 0.2 - 3 \times 10^{19}\ m^{-3}$

4-mm interferometer

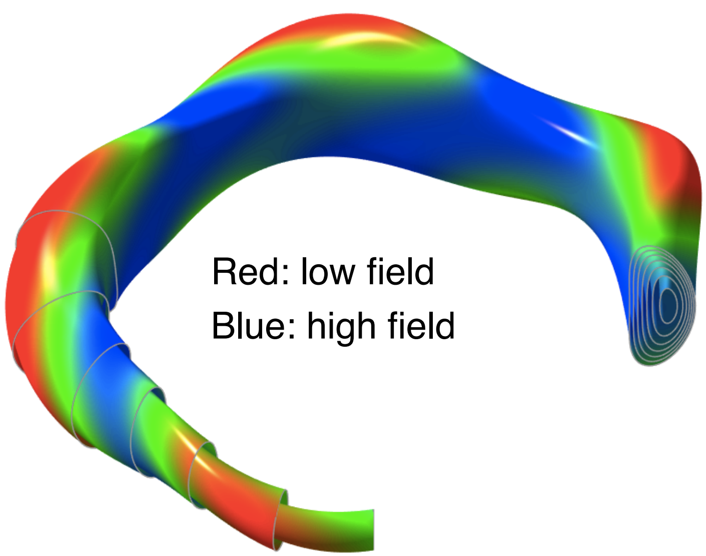
$T_{e0} \sim 300$ eV w/ ohmic current

soft X-ray Bremsstrahlung

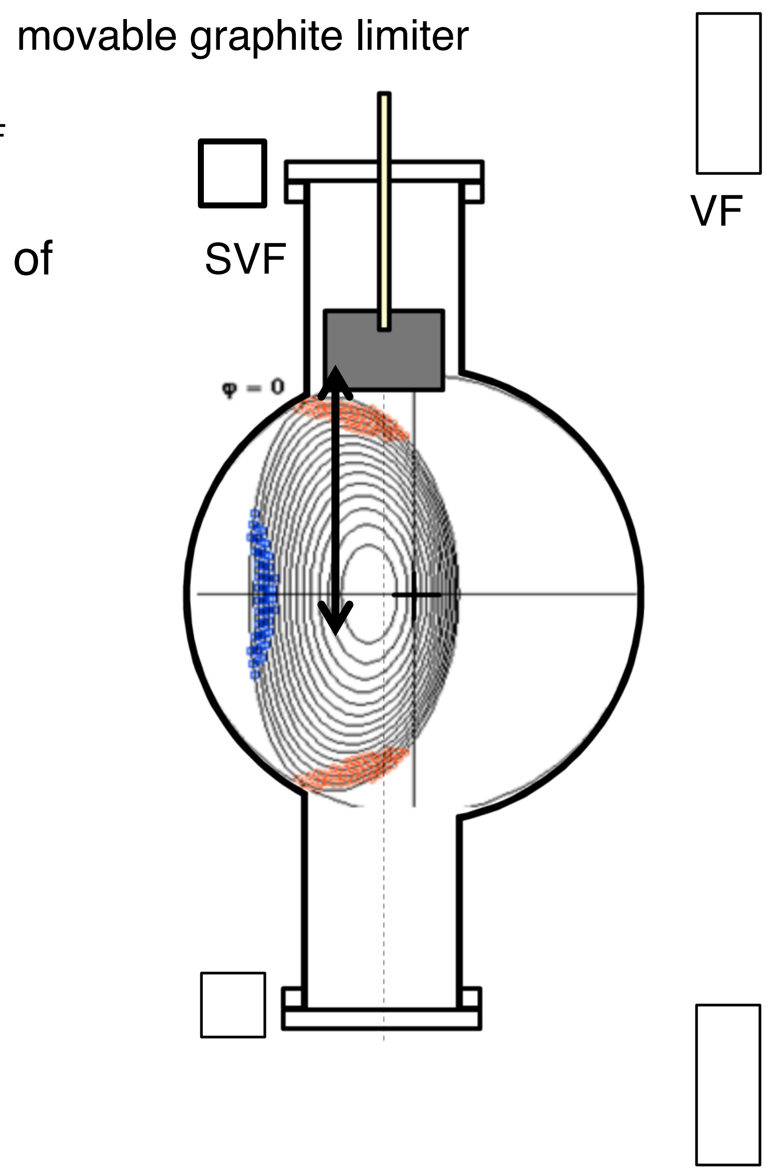


Magnetic geometry is variable

- Vacuum rotational transform varied with I_{TF}/I_{HF}
- Elongation and shear variable with I_{SVF}
- Circular vacuum vessel accommodates range of shapes
- Movable limiter to restrict minor radius
- Ohmic current to add rotational transform



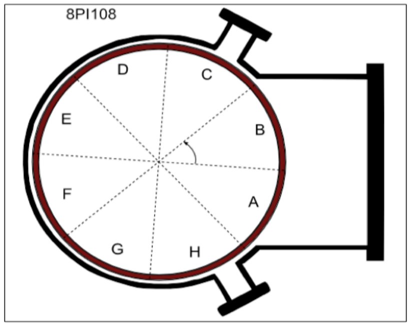
3D equilibrium computed with VMEC



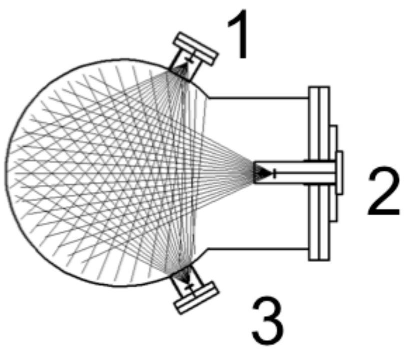
Experimental 3D equilibria reconstructed with V3FIT code

External magnetic diagnostics for reconstruction:

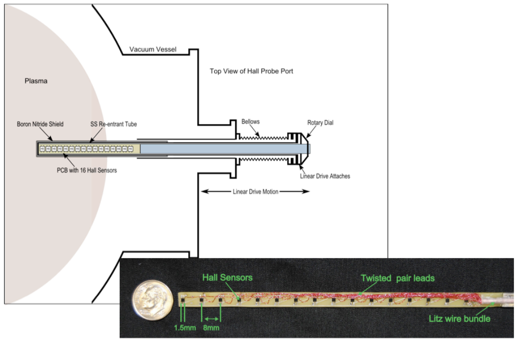
- Multiple partial Rogowskis, local probes for poloidal field
  - compensated for axisymmetric and non-axisymmetric eddy currents
- Poloidal flux saddle coils; local B_r coils
- Diamagnetic flux



Soft X-ray arrays



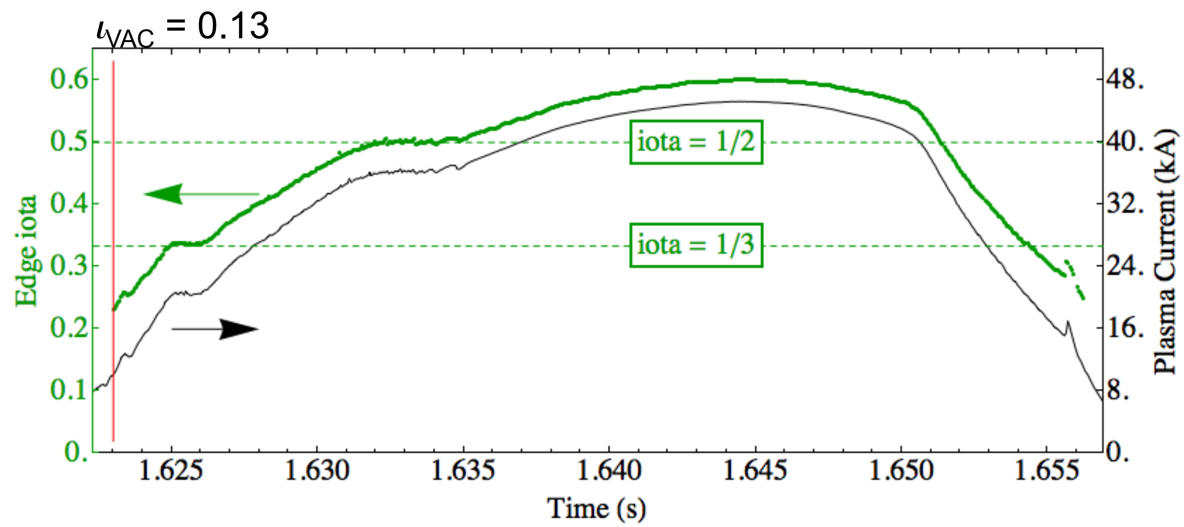
Insertable Hall probe array for internal $B_\theta(r)$

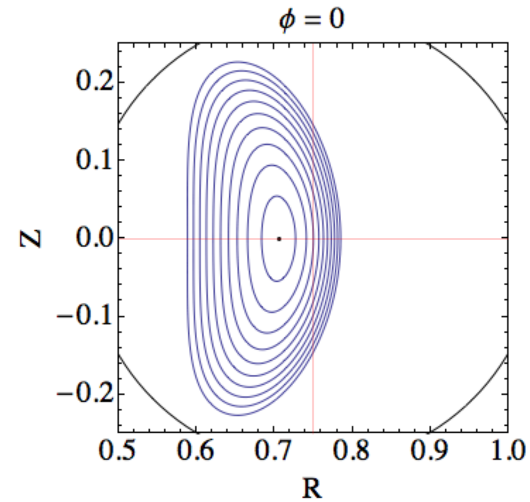


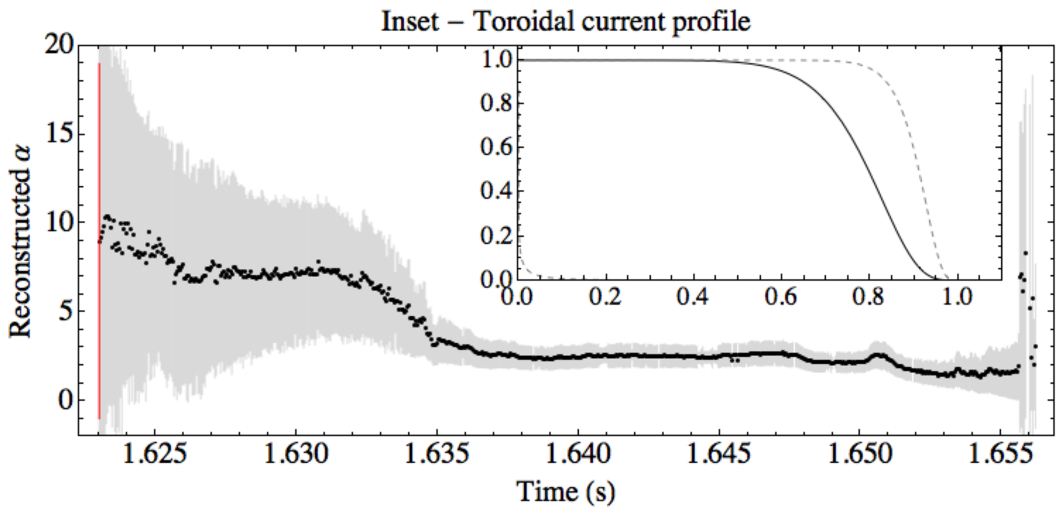
Pressure profile not yet measured

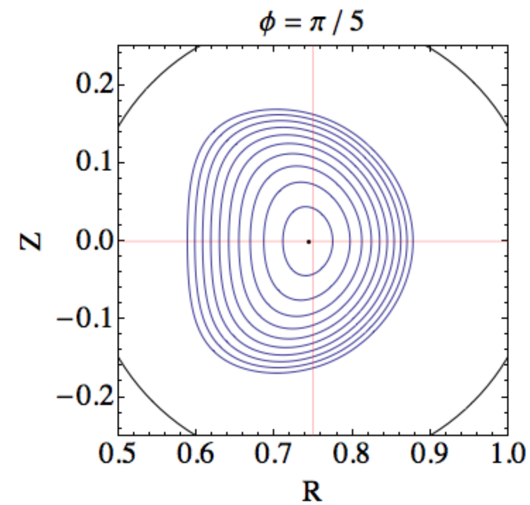
- assumed parabolic

Reconstruction sequence demonstrates evolution of current profile; plasma volume





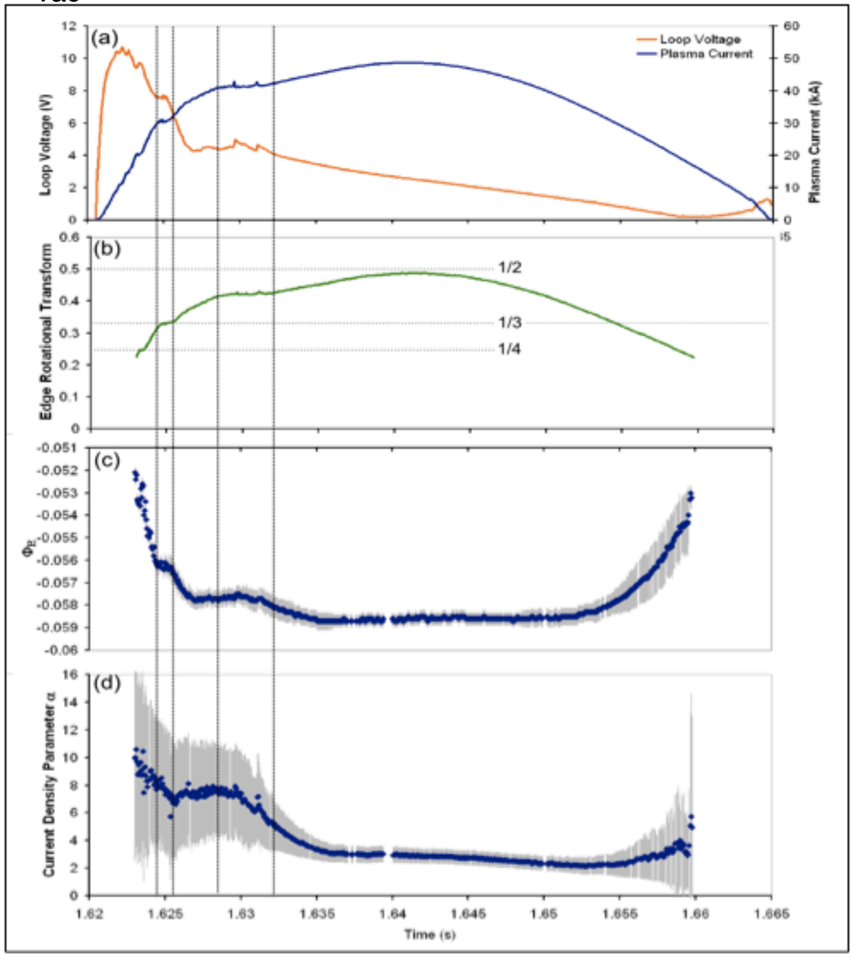




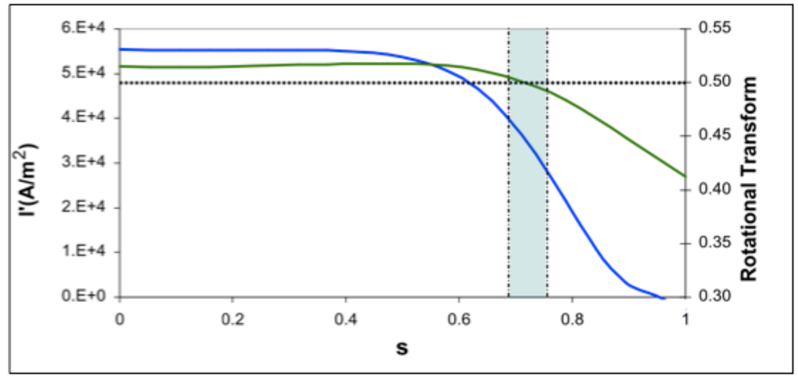
Current profile parameterization: $j(s) = j_0(1-s^{\alpha})^5$

Evolution of current profile is similar for all vacuum rotational transforms

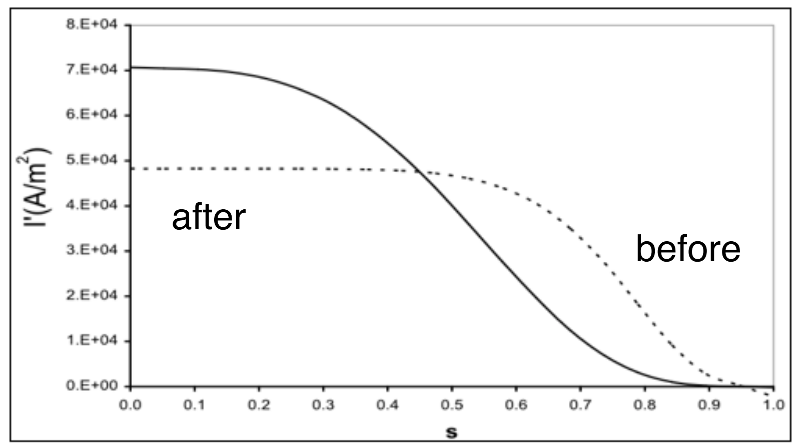
$\iota_{vac}(a)$~0.04



Iota, current profile at $\iota_{TOT}(a)$~ 0.41

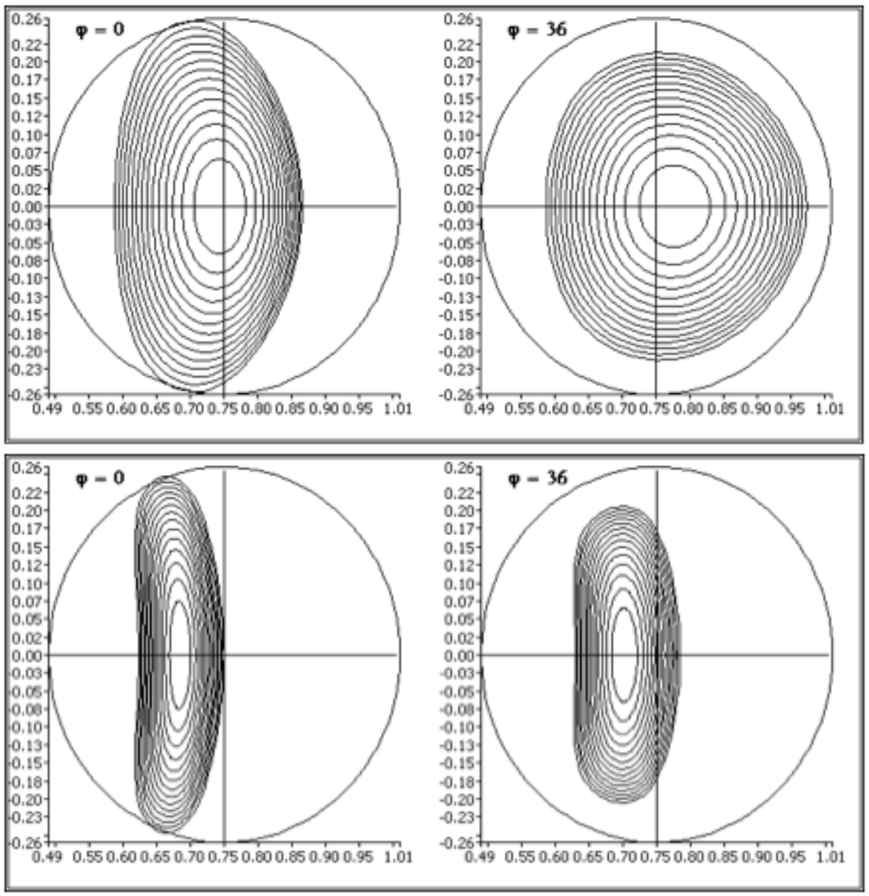


Peaking of current profile at $\iota \sim 0.5$ transition



Vertical field index of hybrid plasma is large, limiting radial motion of plasma during current decay

$\iota_{TOT} = 0.3$



$\iota_{TOT} = 0.04$

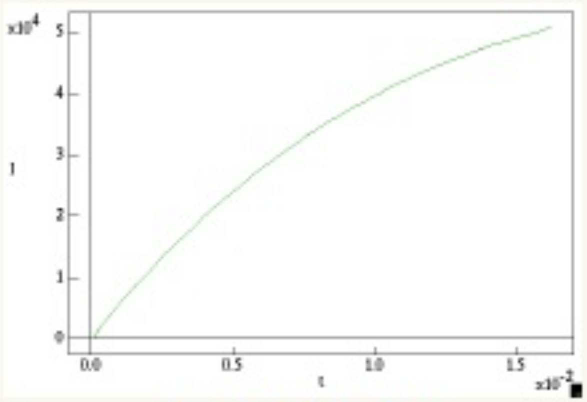
Equilibrium flux surfaces at maximum current

equilibrium flux surfaces pre- and **post-disruption**

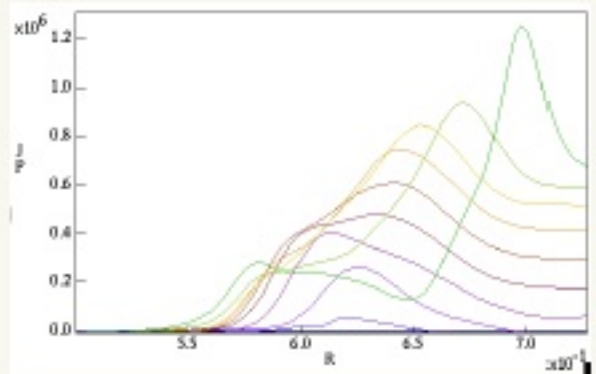
Applied equilibrium VF changes by < 5%

VMEC equilibrium code, S. Hirshman, ORNL, 1986

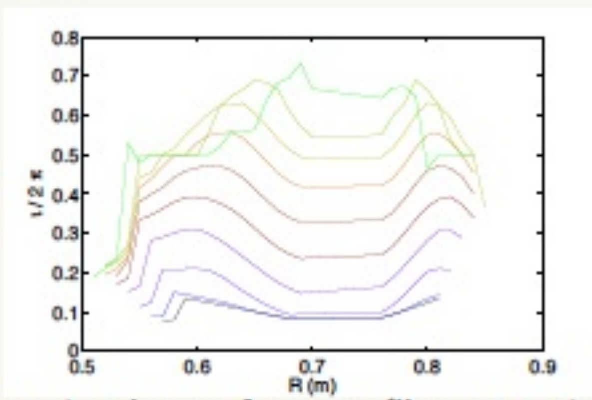
First simulations with NIMROD show behavior similar to experiment



Total current (A).



Current penetration (ϕ-component) at various times (A/m^2).



Rotational transform profiles at various times.

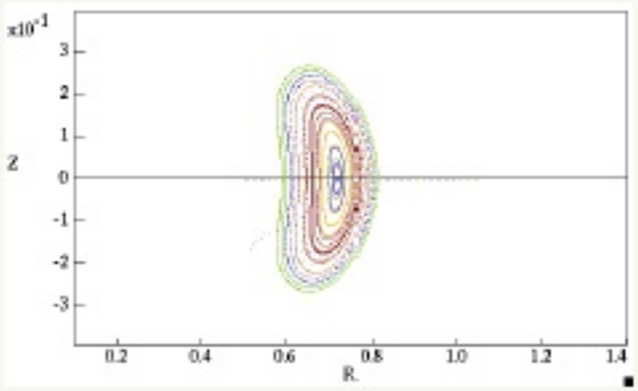
- Mag axis at 0.725m. Sx from 0.60m (t=0) to 0.54m (t=16ms).
- Hollow current profile.
- Rotational transform profiles become somewhat hollow.
- m=2,n=1 structure forms late in time.

APS-DPP Nov 2011

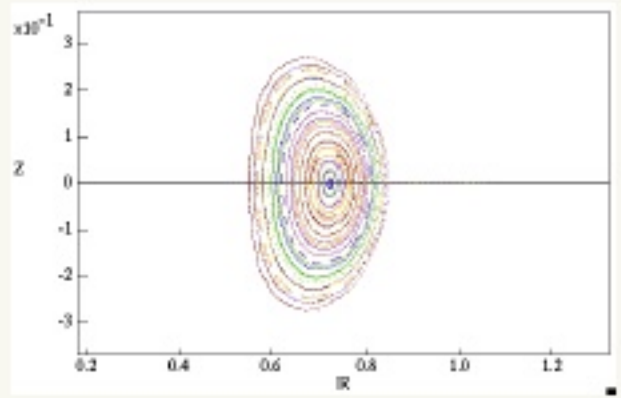
V_{loop} = 4V constant, fixed resistivity

Schlutt, Hegna, Sovinec et al., 2011

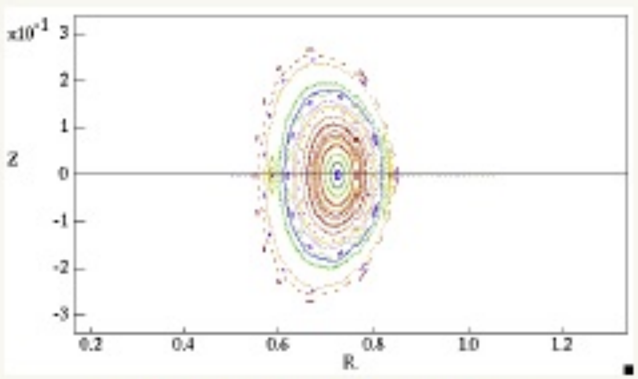
Growing m=2/n=1 island found by NIMROD leads to collapse at t > 16 msec



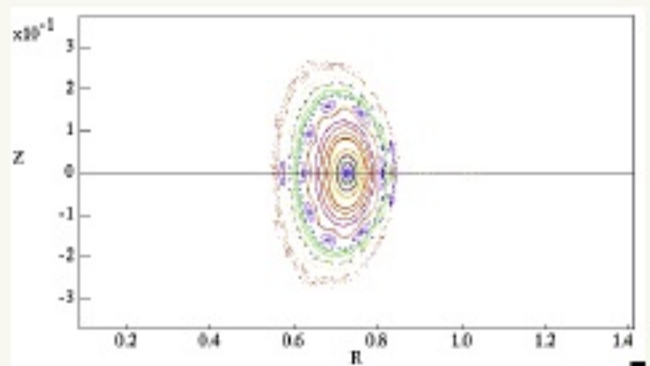
Poincaré plot for t=0.



Poincaré plot for t=9ms.

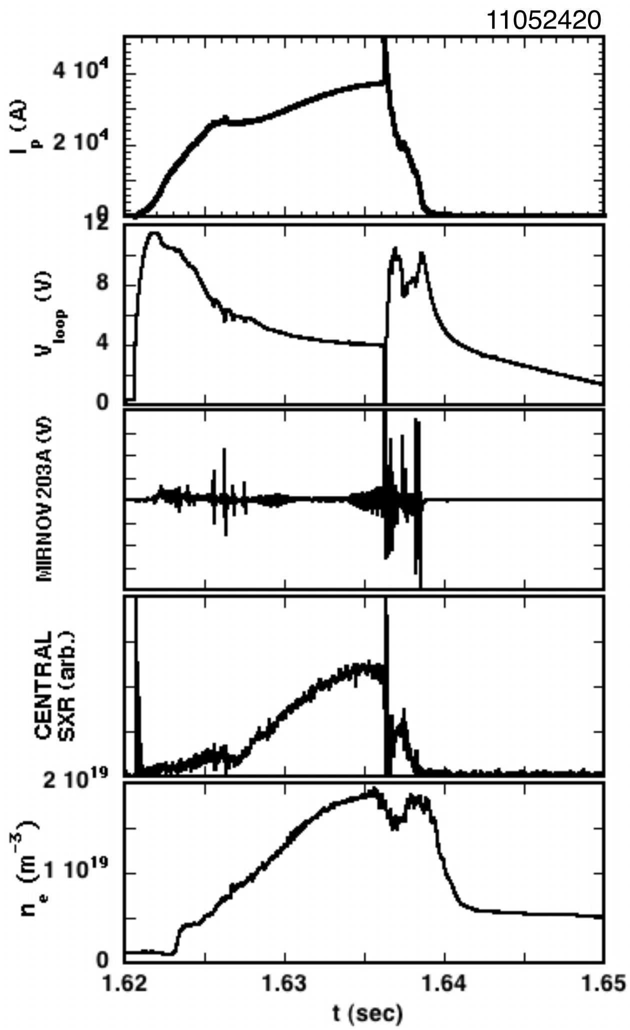


Poincaré plot for t=12ms.

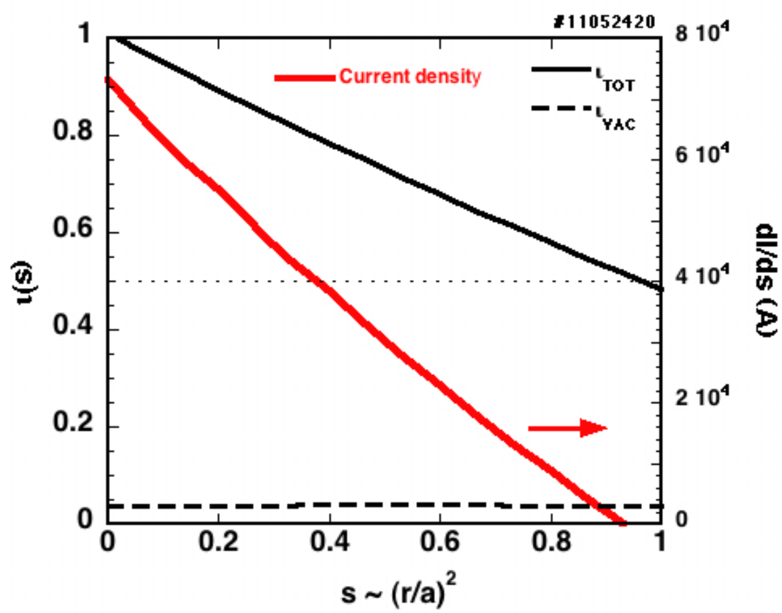


Poincaré plot for t=14ms.

Disruptions can be triggered by various means at low vacuum transform

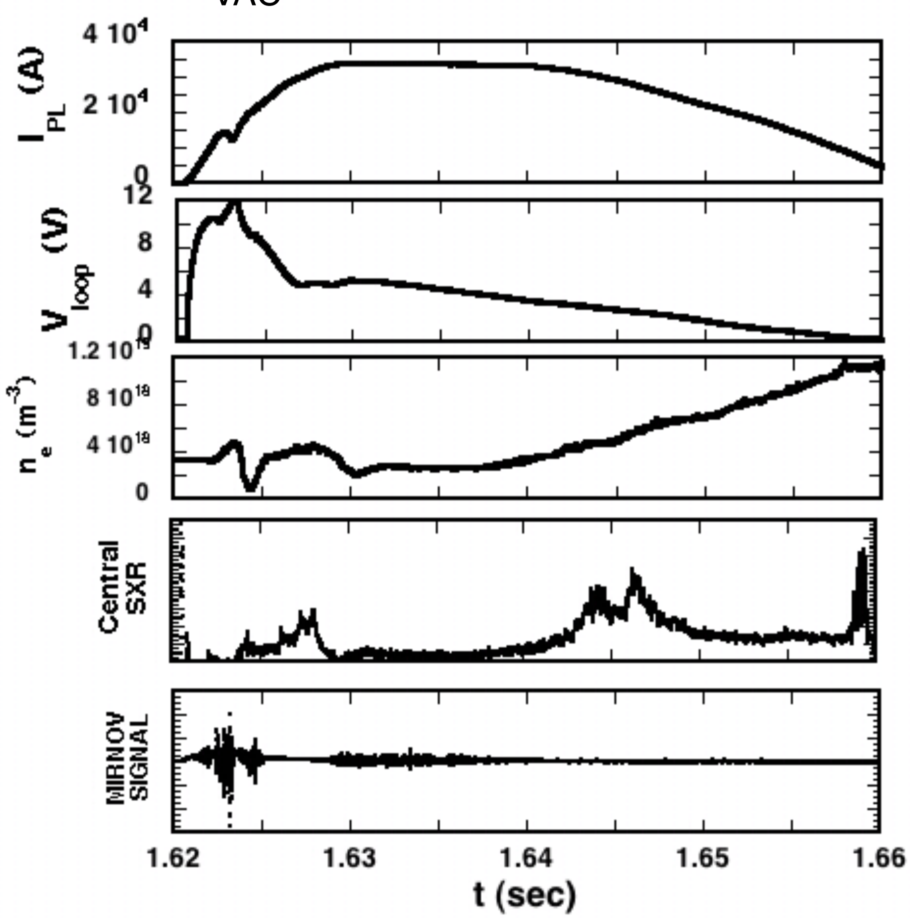


- This disruption preceded by growing m=2 and m=3 tearing modes
- Edge transform ι(a) just below 0.5 in sawtoothing discharge
- Easier to trigger with higher density
- Most disruptions with clear precursors seem consistent with cylindrical 1-D tearing mode model (with independent iota & j profiles)



Discharges with high vacuum transform appear bounded by ι <1

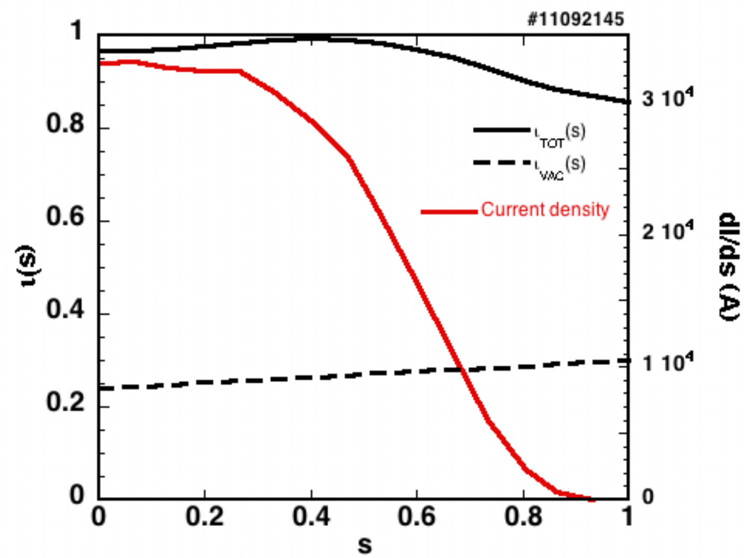
$\iota_{VAC} = 0.3$



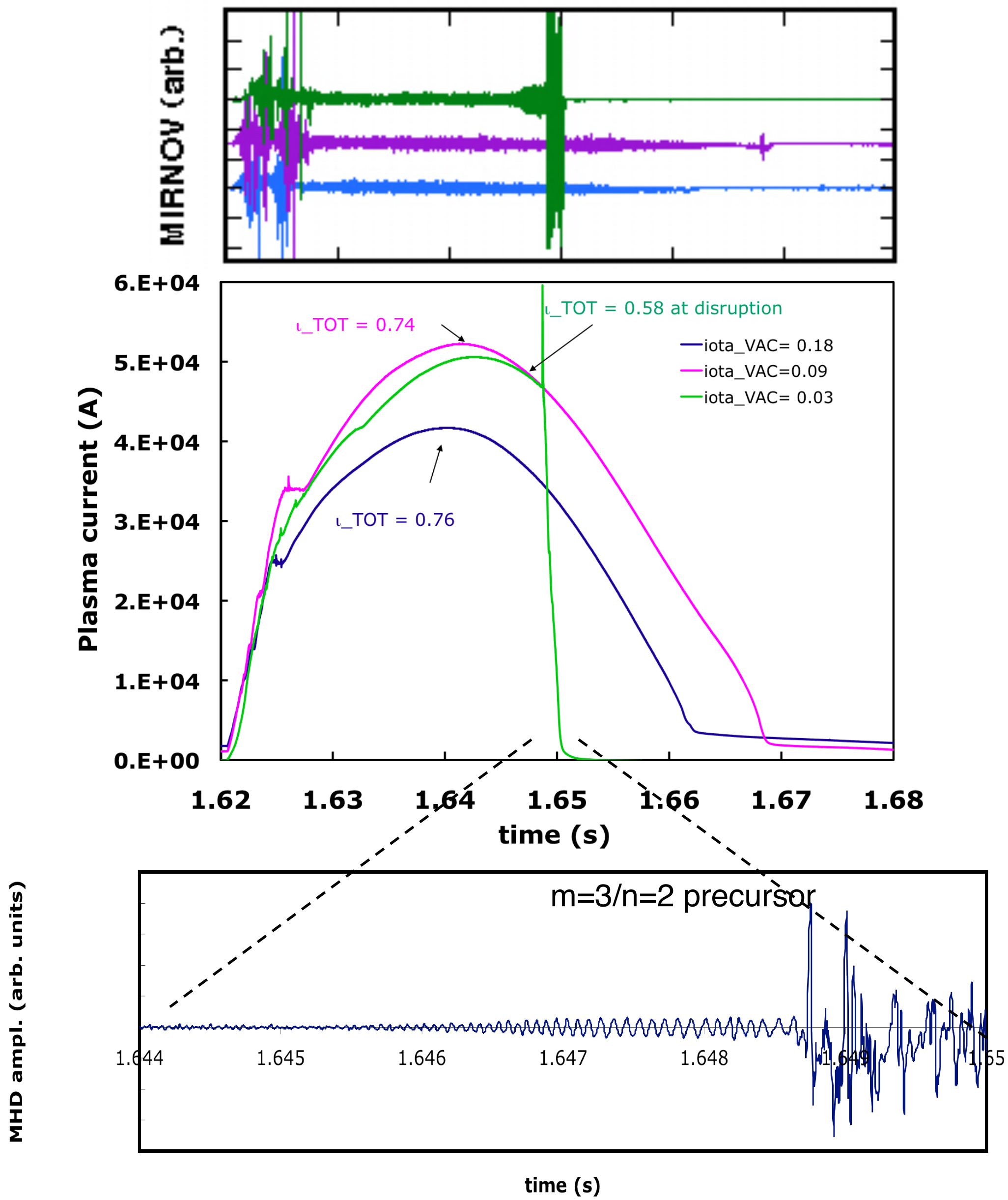
Discharge quiescent for $\iota_{TOT}(a) > 0.5$

Severe density loss at $\iota_{TOT}(a) \sim 0.5$

Current "clamped" to limit $\iota < 1$

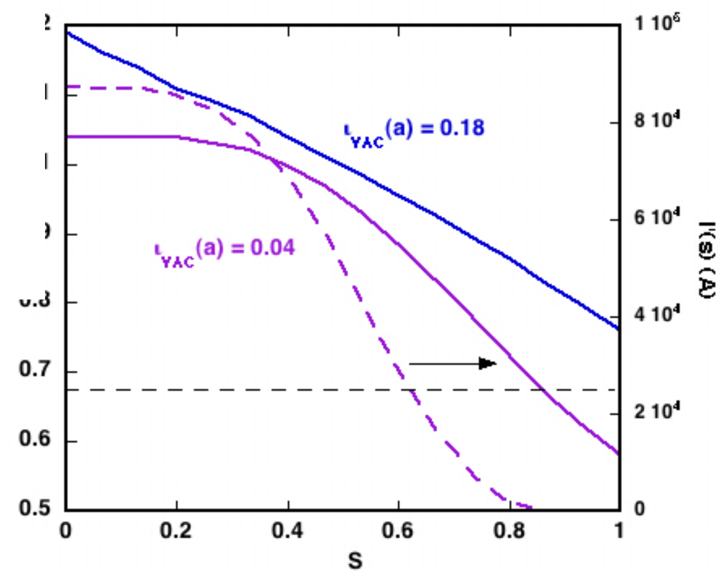


Discharges in CTH disrupt only at low vacuum field transform

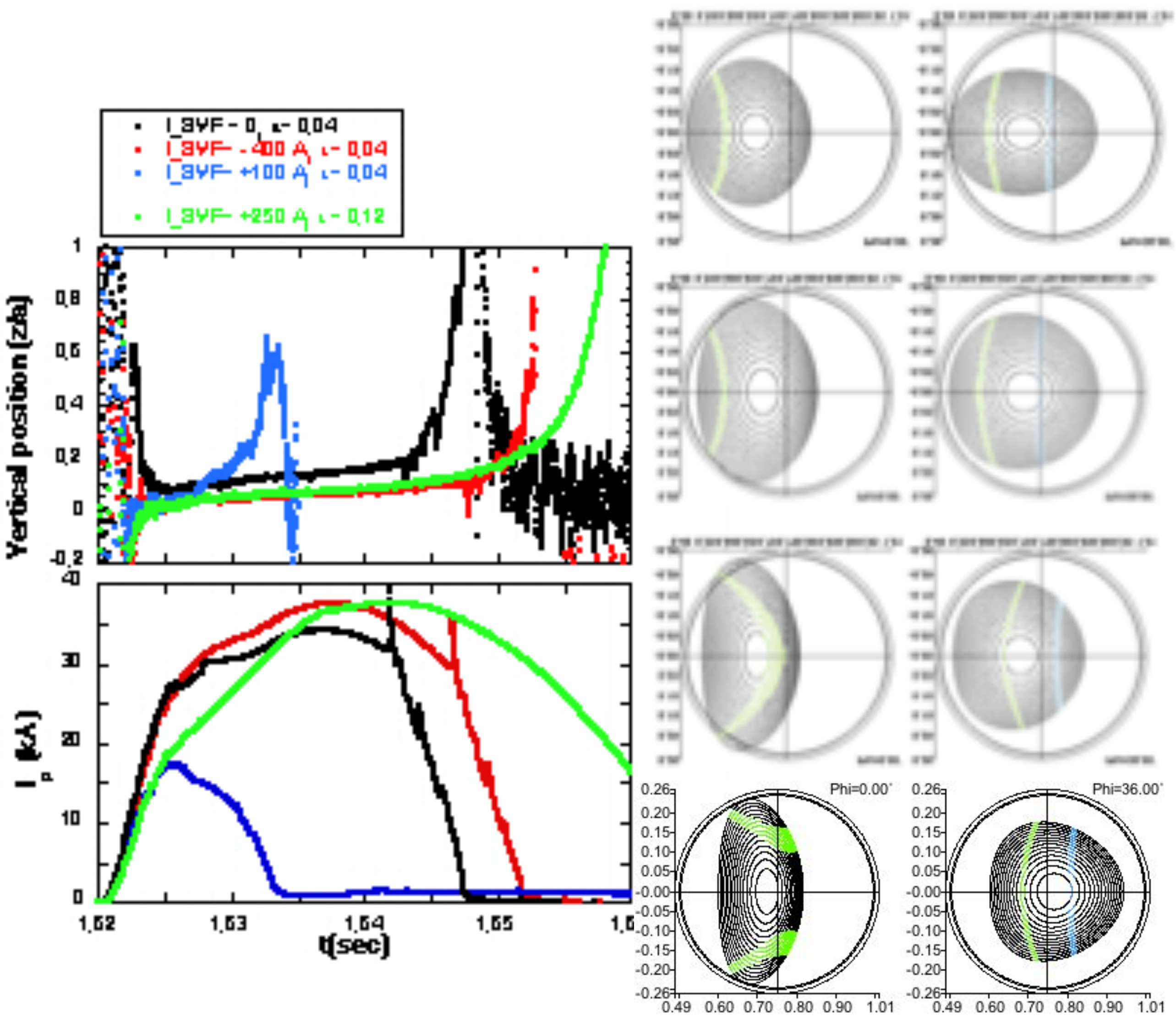


All discharges show resonant MHD before crossing rational ι(a); e.g. m/n = 2/1 for ι(a) approaching 0.5

Disruptions generally preceded by growing MHD oscillations



Vertical stability depends on elongation and vacuum transform



LOW ELONGATION
κ = 1.22;
I_{SVF} = -450 A

MOD. ELONGATION
κ = 1.35;
I_{SVF} = 0 A

HIGH ELONGATION
κ = 1.6;
I_{SVF} = +100 A

HIGH ELONGATION
κ = 1.72;
I_{SVF} = +250 A

High vacuum transform

Passive vertical stability predicted to improve with fraction of vacuum transform

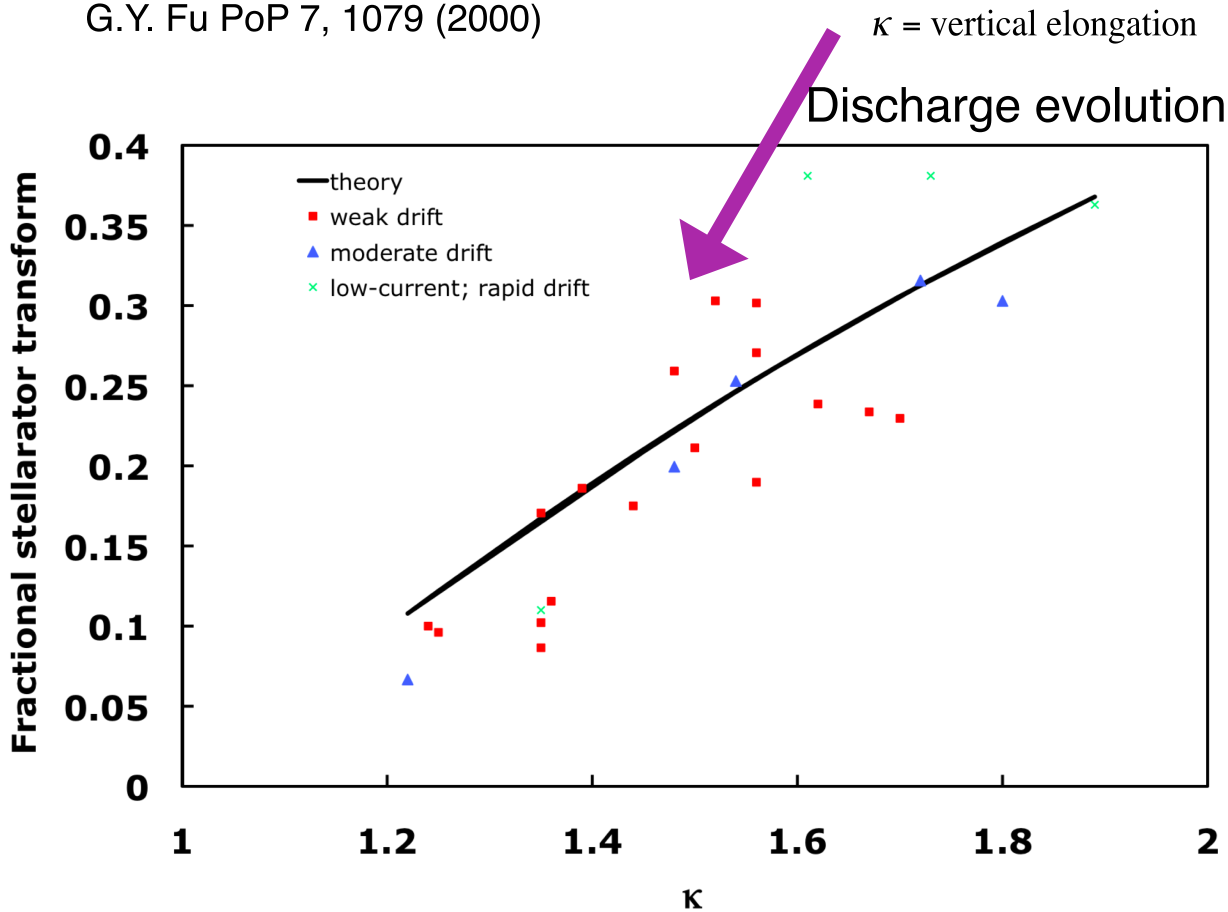
Poloidal field of stellarator equilibrium can passively stabilize vertical drift.

analytic condition for vertical stability of current carrying stellarator plasma from ideal MHD:

$$f \equiv \frac{\iota_{VAC}(a)}{\iota_{TOT}(a)} \geq \frac{\kappa^2 - \kappa}{\kappa^2 + 1}$$

κ = vertical elongation

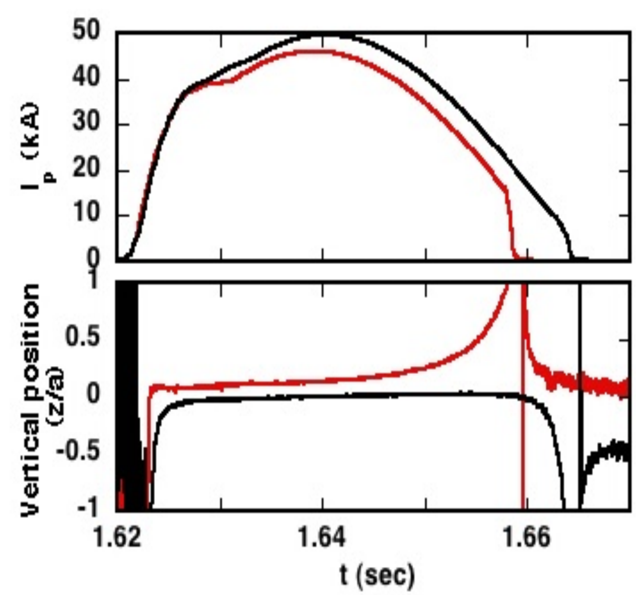
G.Y. Fu PoP 7, 1079 (2000)



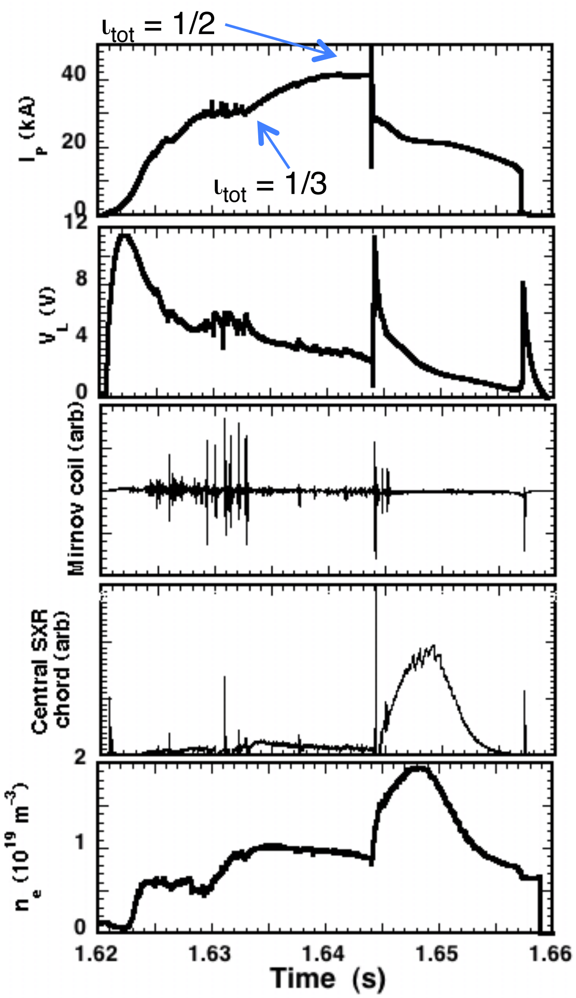
Discharge evolution

Active (programmed) horiz. field

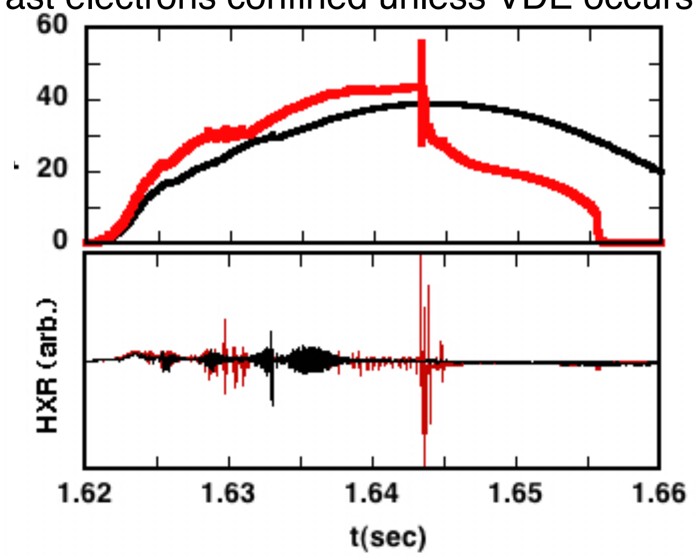
Compensates small n=0 error field to maintain vertical position



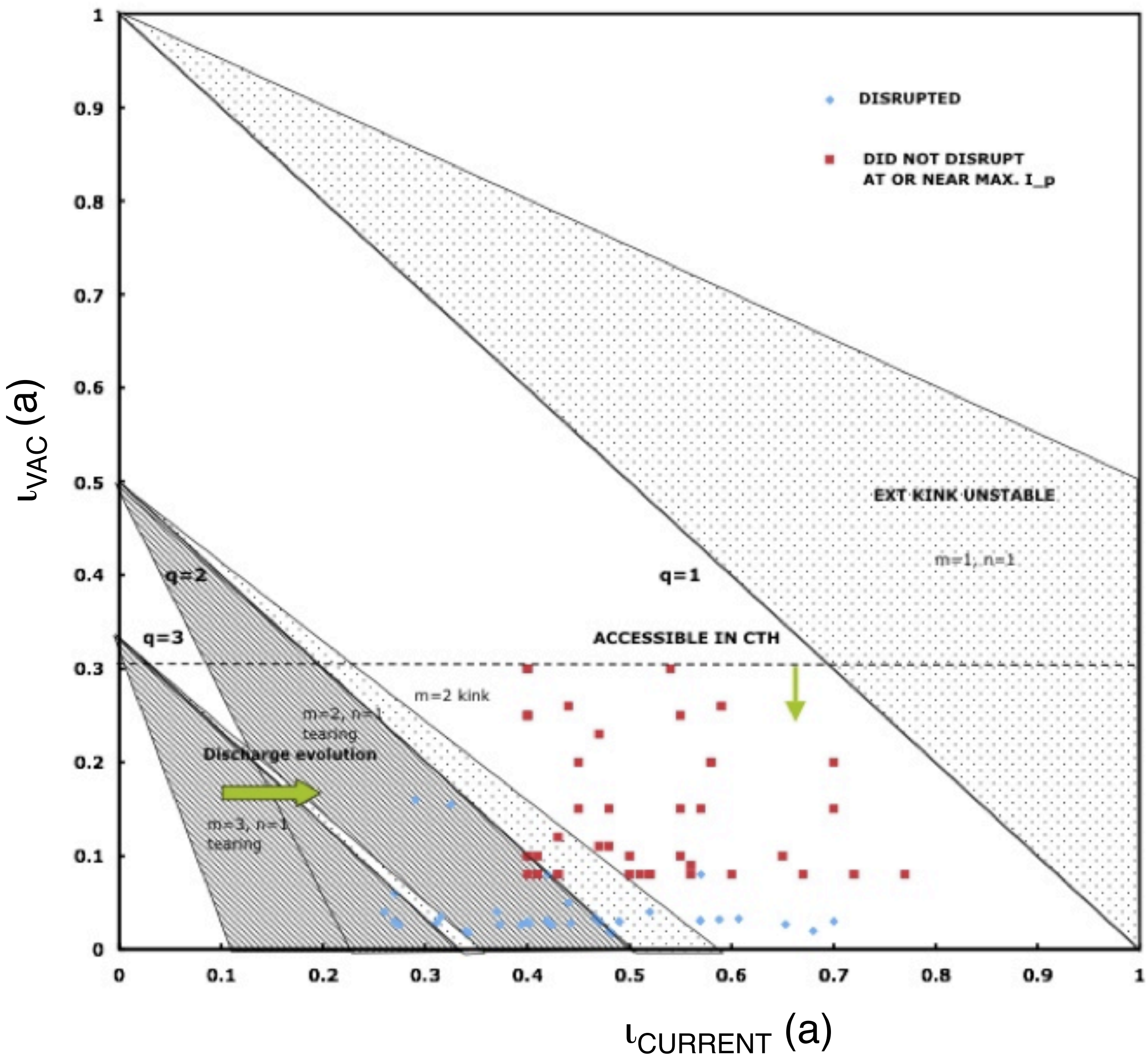
With compensation of vertical drift, disruptions are usually incomplete



- Disruptions still occur only at lowest values of external transform; in this case $\iota_{VAC} \sim 0.04$
- Low-q, low density disruptions can occur without growing though sometimes with bursty m=2 precursor.
- Plasma often recovers without complete disruption
  - Density increase
  - Sawtoothing discharge
  - Fast electrons confined unless VDE occurs



Most disruptions in hybrid discharges occur for $\iota_{VAC} < 0.1$



Regions of instability indicated in "cartoon" form

Depend on profiles of current and vacuum rotational transform

Based on 1-D Euler eq. for perturbed flux

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\psi}{dr}\right)-\frac{m^2}{r^2}\psi-\left(\frac{mr}{m\iota(r)-n}\right)\frac{\mu_o R_o}{B_o}\frac{dj}{dr}\psi=0$$

Flat (l =2) stellarator profiles; based on figure from Matsuoka et al, NF (1977)

Free energy of ideal kink and resistive tearing modes altered by stellarator transform

Even in hybrid stellarator/tokamak, the plasma current profile j(r) is partially decoupled from the rotational transform profile ι(r)

Allows for positioning of current profile gradients away from dangerous field line resonances using external fields.

Requires knowledge of actual current profiles and rotational transform profiles in experimental plasmas.

Approach may give some insight in low-beta plasmas.

Conclusions

- Hybrid operation of a tokamak with modest stellarator fields leads to elimination of disruptions in CTH.
  - Disruptions not observed for $\iota_{VAC} > 0.08$, or $\iota_{VAC}/\iota_{TOT} \geq 0.12$
  - Discharges with $\iota_{tot} \geq 0.5$ regularly obtained.

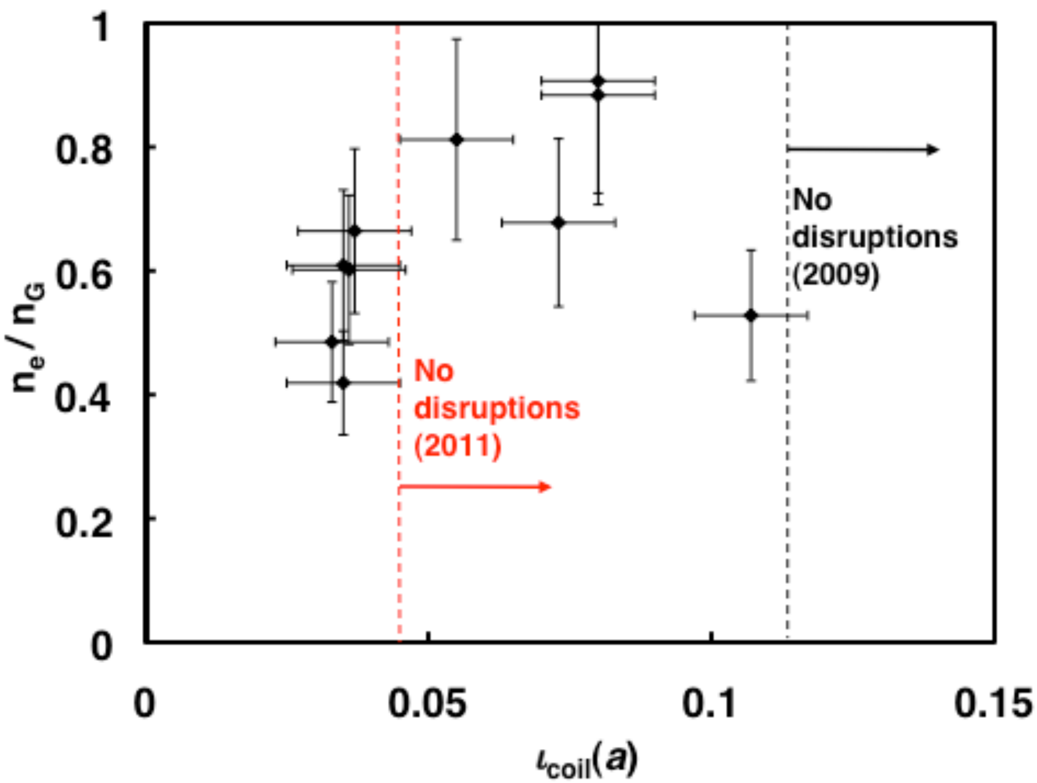
- Final ohmic current profiles are narrow in CTH; broad profiles during current rise are unstable at all vacuum transforms.

  Should lead to lower stability in finite-beta plasmas with bootstrap current.

- VDEs reduced with finite vacuum transform, in agreement with theory.
- Density-limit disruptions remain an interesting target of investigation.

Disruptions disappear as stellarator transform is raised

Density at which disruptions occur vs. stellarator transform



"Disruptions will essentially have to be eliminated" in ITER

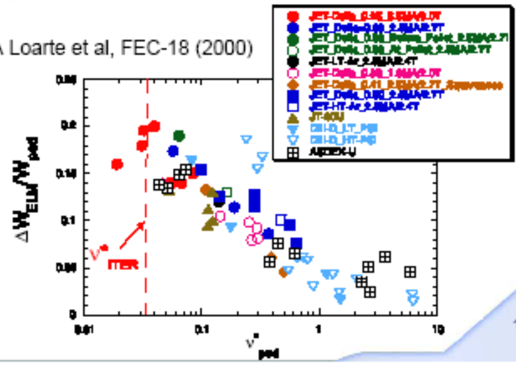
EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

Power Exhaust/ Impurities III

- Transient events are of even greater significance than in ITER
  - availability and first wall lifetime considerations set severe limitations on frequency and magnitude of pulsed events
- Disruptions will essentially have to be eliminated
  - typical estimates in literature set frequency at 0.1 -1 per year
  - issues:
    - thermal quench: ~ 1GJ
    - current quench: ~ 1GJ
    - runaway electrons: >10MA if not suppressed
- ELMs too will essentially have to be eliminated
  - ELM-enhanced erosion might already set PFC lifetime limits in ITER

  ⇒ ELM control/ suppression techniques

A Loarte et al, FEC-18 (2000)



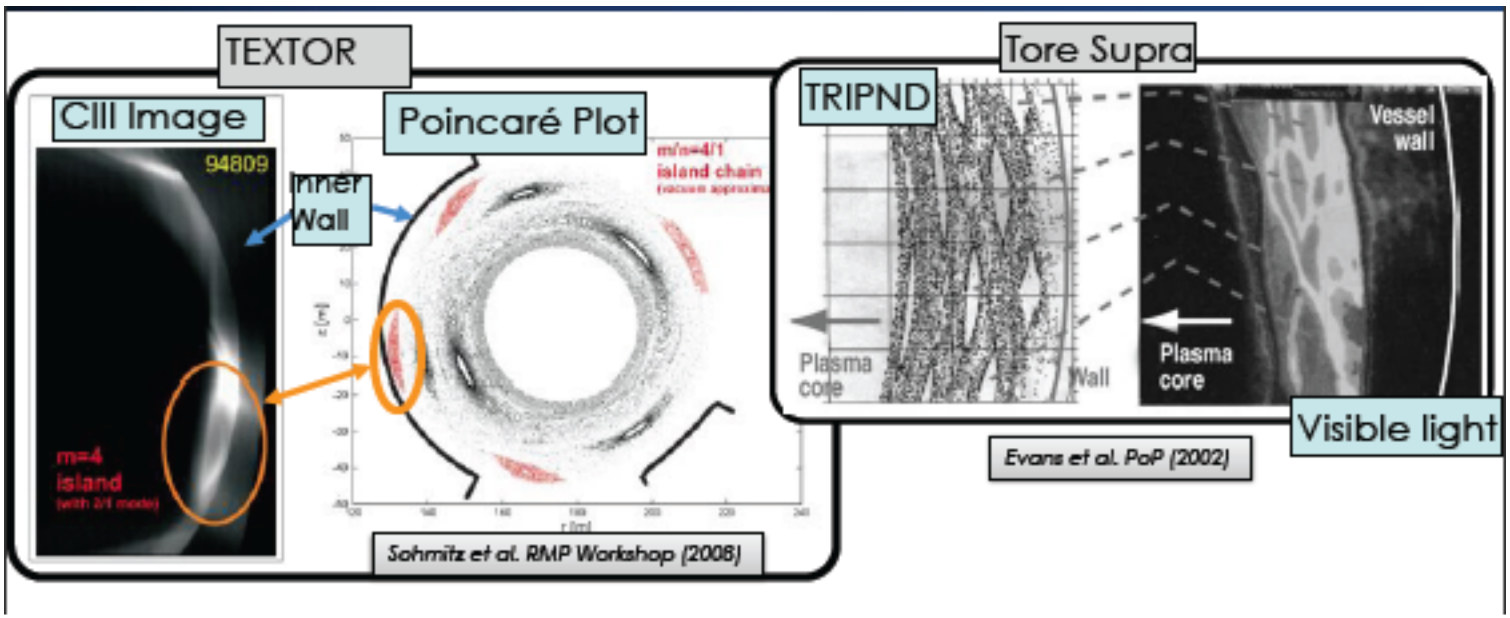
D. Campbell et al.
IAEA 2006, Chengdu
"Critical Issues for Tokamak Power Plants"

- Aries reactor studies: disruptions must be < 1 per year.
- Approximately 10% of discharges in large tokamaks disrupt due to:
  - high density
  - high currrent (low-q)
  - high β
  - MHD mode-locking
  - impurity influx
  - equipment/operator failure
  - mysteries

How to predict, avoid, or mitigate disruptions at high β in advanced tokamak scenarios with high bootstrap current?

What is role of magnetic islands in MHD equilibrium & stability of stellarators and tokamaks?

- Role of 3D non-axisymmetric fields in toroidal confinement of increasing interest
- Plan to image islands in CTH using impurity light



•M. Shafer, 2009