Plasma disruption avoidance using non-axisymmetric shaping with stellarator fields

David Maurer

M.C. ArchMiller, M.R. Cianciosa, D.A. Ennis, J.D. Hanson, G.J. Hartwell, J.D. Hebert, J.L. Herfindal, S.F. Knowlton, X. Ma, M.D. Pandya, N.A. Roberds, and P.J. Traverso

AUBURN UNIVERSITY

# Disruption avoidance and mitigation essential for future current carrying tokamaks

- Context: Small amounts of 3D fields are used for a variety of purposes on present day tokamaks with $B_{3D}/B_0 \sim 10^{-3}$

- Can application higher levels of 3D magnetic shaping, $B_{3D}/B_0 \sim 0.1$, suppress tokamak instabilities and disruptions?

Work informs experimental basis for:

--- Stability properties of compact quasi-axisymmetric stellarators
   A. Reiman, et al, Physics of Plasmas (2001)

--- Possible use of external transform on tokamak systems
   L. P. Ku and A. Boozer, et al, Physics of Plasmas (2009)

--- Shed light on tokamak disruption physics and 3D MHD

# Compact Toroidal Hybrid (CTH) designed to address strong 3D shaping effects on MHD instabilities & disruptions

- **Hybrid**: current driven within 3D equilibrium of a stellarator plasma

- Can vary the relative amount of externally applied transform

  - I_p provides up to 95%

- Previous hybrid stellarators showed evidence of disruption avoidance and improved positional stability

  (D. W. Atkinson, et al, Phys. Rev. Lett. (1976), H. Ikezi et al, Phys. Fluids (1979), W7-A team, Nucl. Fusion (1980), K. Sakurai and S. Tanahashi, J. Phys. Soc. Jpn. (1980)
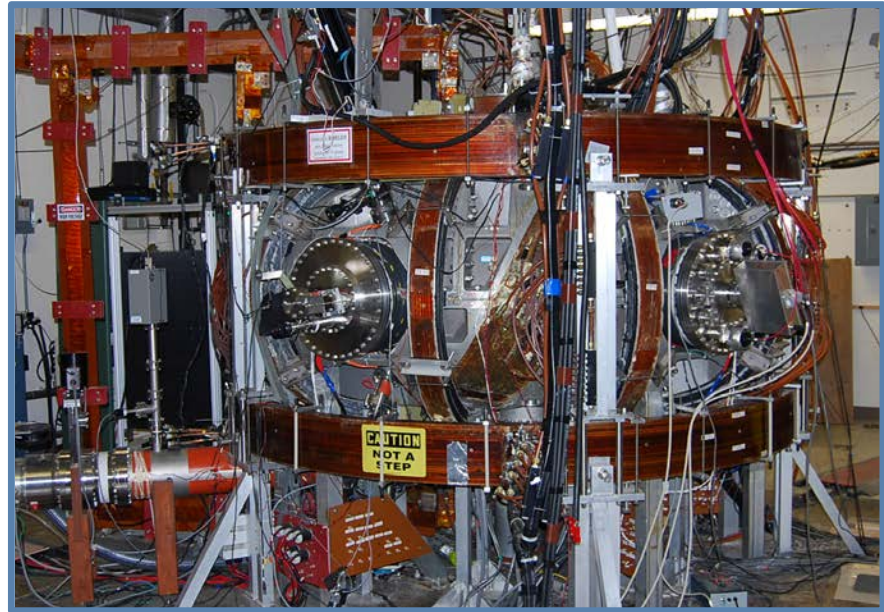
Disruptive behavior reproducibly modified by modest levels of vacuum transform

- Amount of vacuum transform required and the character of the observed disruption suppression depend on the type of disruption

- Three disruption types investigated in CTH:

  - Vertically unstable plasmas

  - Density limit disruptions

  - Low-q disruptions

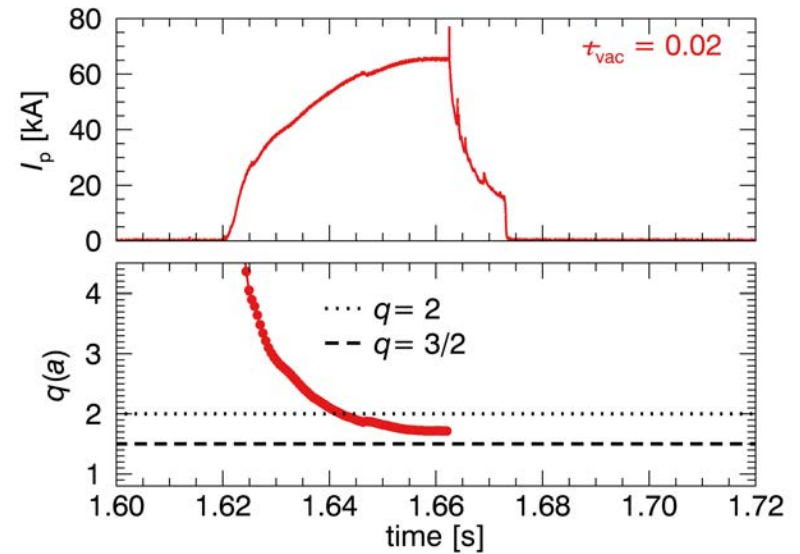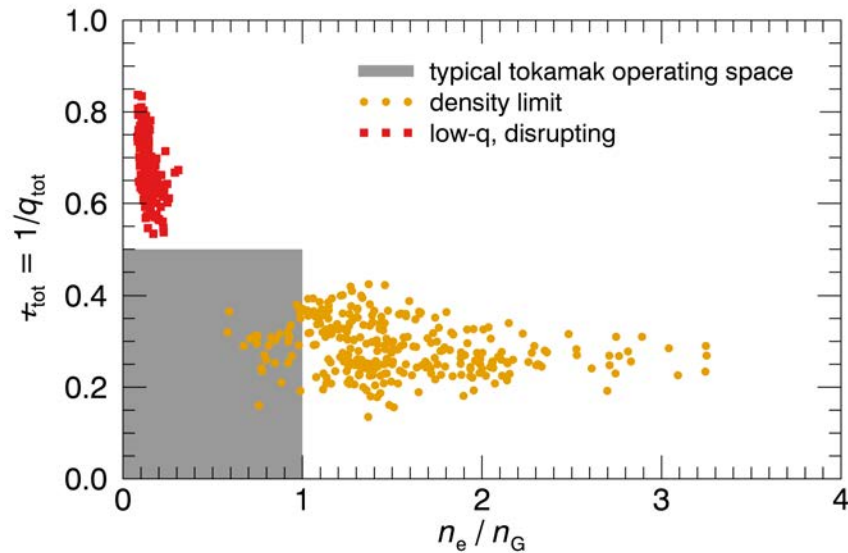# Overview of CTH operational space and three types of disruptions observed
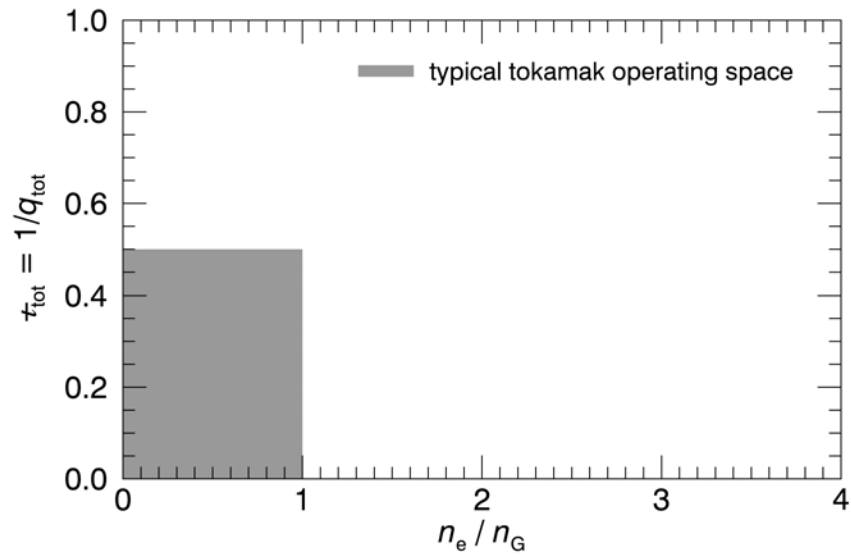
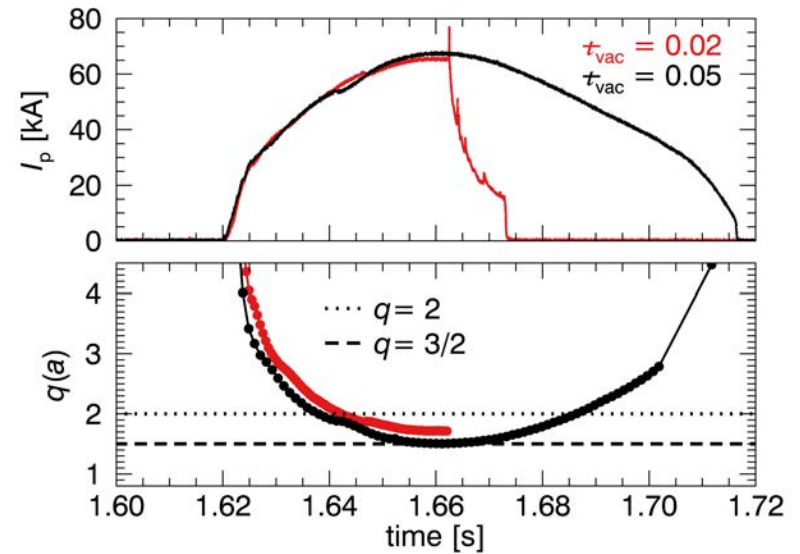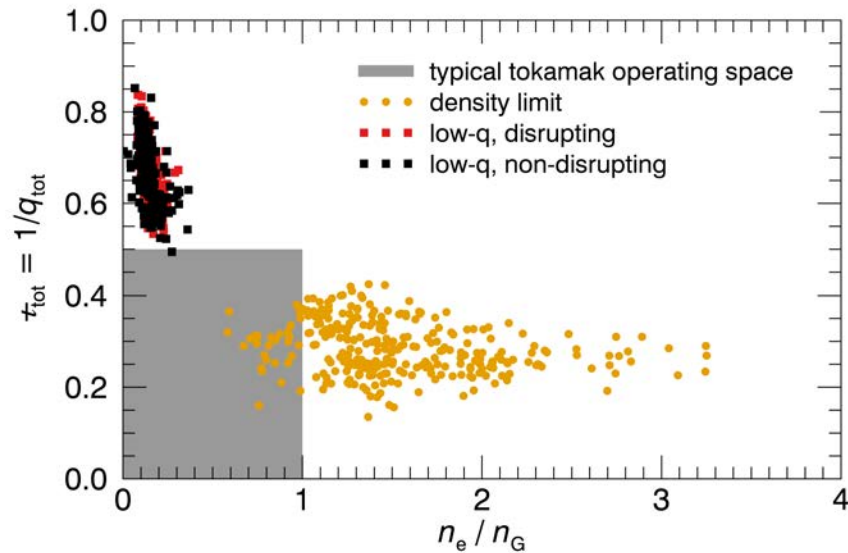# CTH can operate beyond the Greenwald density limit
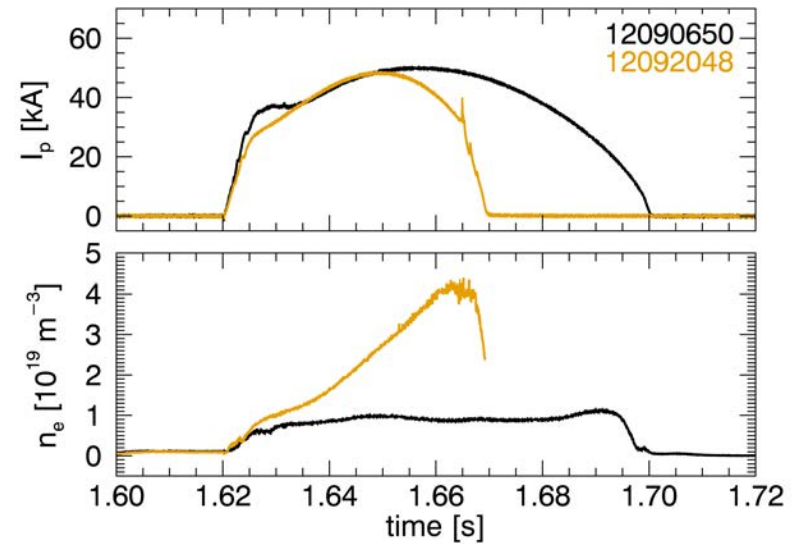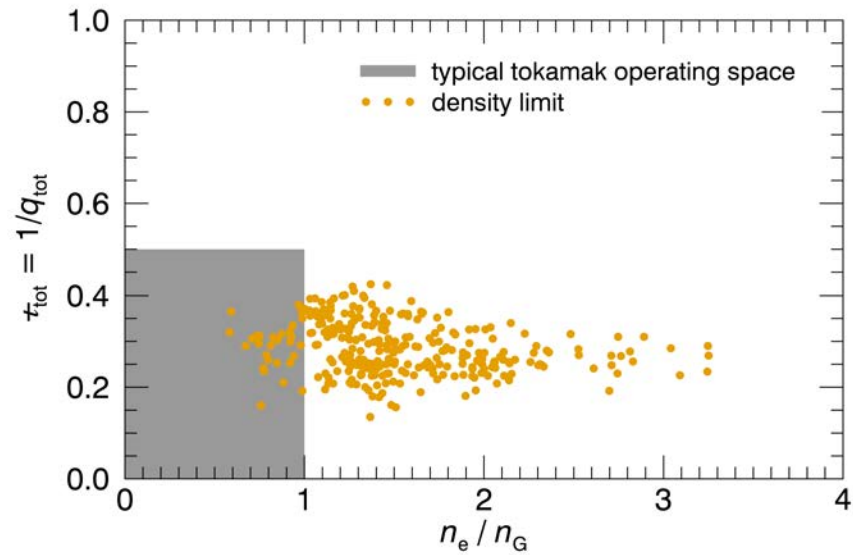
- Density-limit disruptions

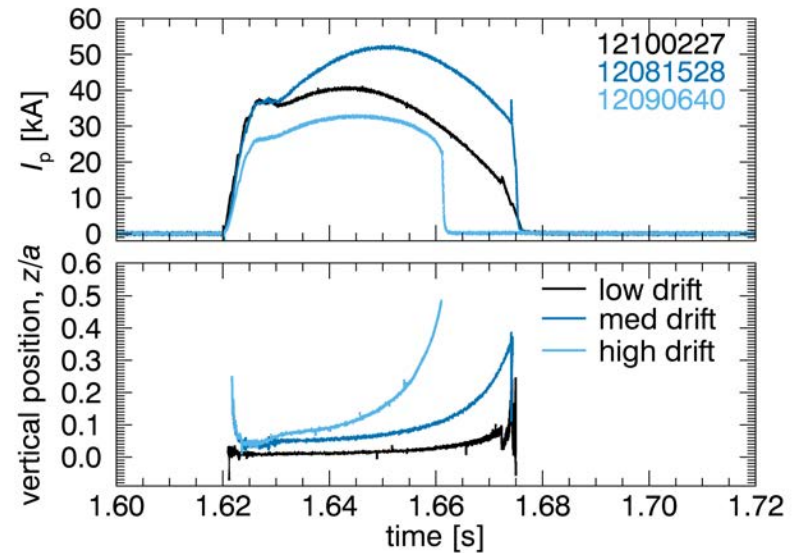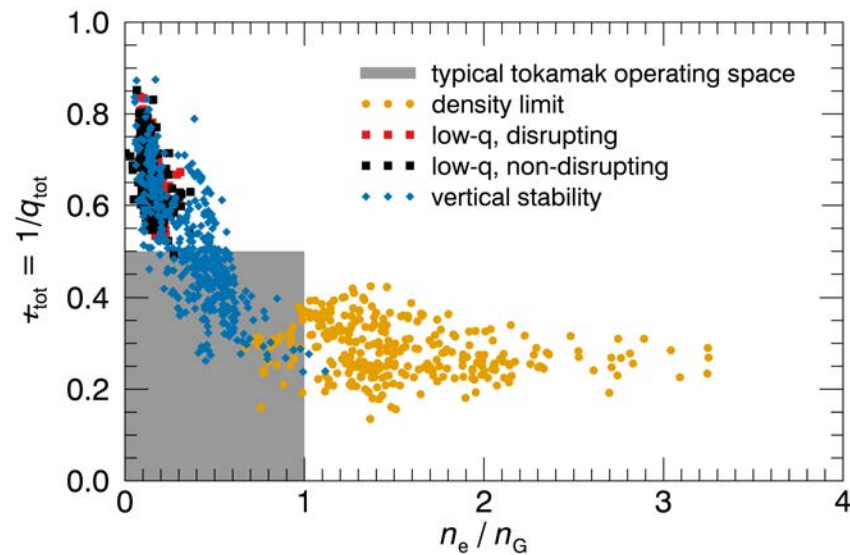# Low-*q* disruptions can occur when CTH operates with *q*(*a*) < 2

- Density limit disruptions

- Low-*q* disruptions

CTH can operate beyond the $q(a) = 2$ current limit, with a slight increase in t_{vac}

- Density limit disruptions

- Low-q disruptions

Vertically unstable plasmas can result in a disruption if uncompensated

- Density limit disruptions
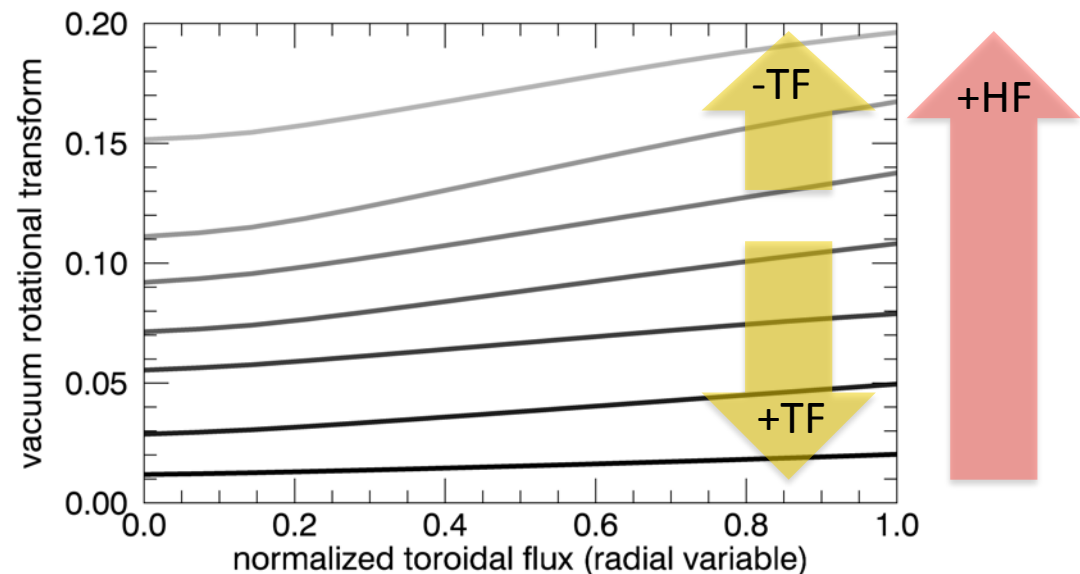- Low $q(a)$ disruptions
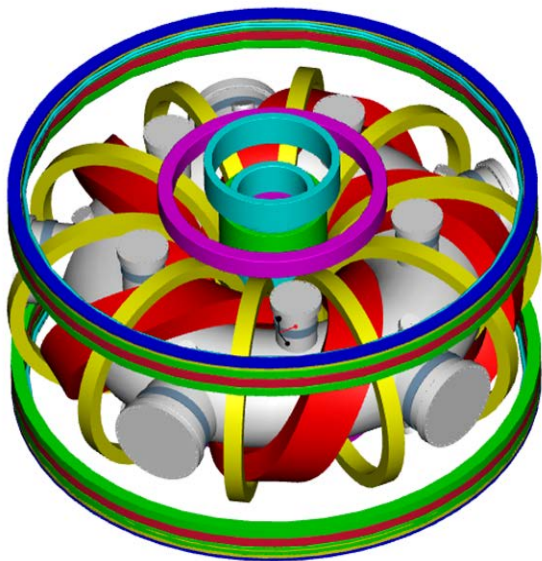- Vertically unstable plasmas

Outline

- Compact Toroidal Hybrid

- 3D equilibrium reconstruction

- Disruption avoidance:

  1. Vertically unstable plasmas
  2. Density limit disruptions
  3. Low-q disruptions

- Summary

# CTH: Flexible magnetic configuration with vacuum transform variable by factor of 10

- **Helical Field coil** and **Toroidal Field coil** currents adjusted to modify vacuum rotational transform: $0.02 < t_{vac} < 0.03$
- **Shaping Vertical Field coil** varies elongation κ and shear
- **Trim Vertical Field coil** and **Radial Field coil** control position

$R_0 = 0.75$ m $R/a \sim 4$ $n_e \leq 5\times10^{19}$ m^{-3} $T_e \leq 150$ eV $|B| = 0.5$ T

CTH: With up to 95% of the rotational transform from plasma current

- **Helical Field coil** and **Toroidal Field coil** currents adjusted to modify vacuum rotational transform ι_{vac}
- **Shaping Vertical Field coil** varies elongation κ and shear
- **Trim Vertical Field coil** and **Radial Field coil** control position
- **Central solenoid** drives $I_p \leq 80$ kA, dominating total transform

$R_0 = 0.75$ m $R/a \sim 4$ $n_e \leq 5\times10^{19}$ m^{-3} $T_e \leq 150$ eV $|B| = 0.5$ T
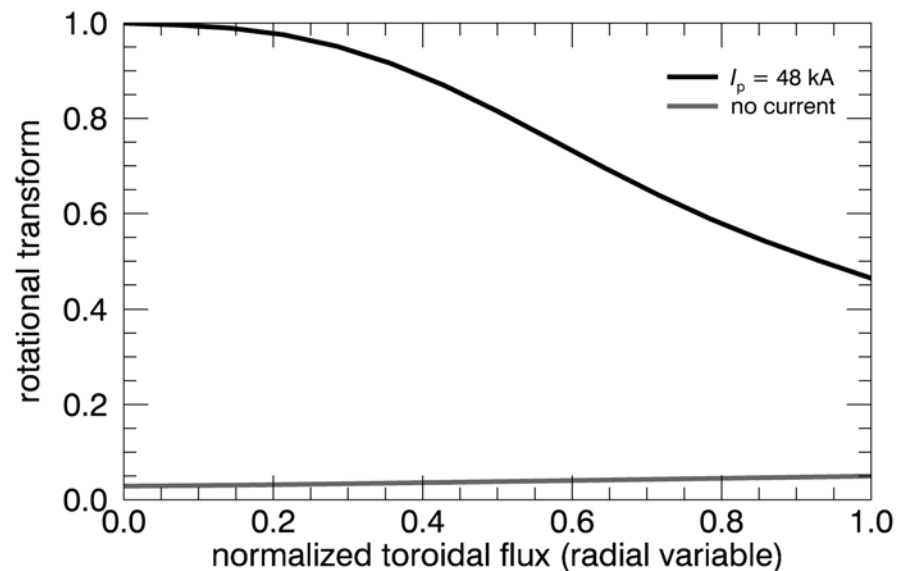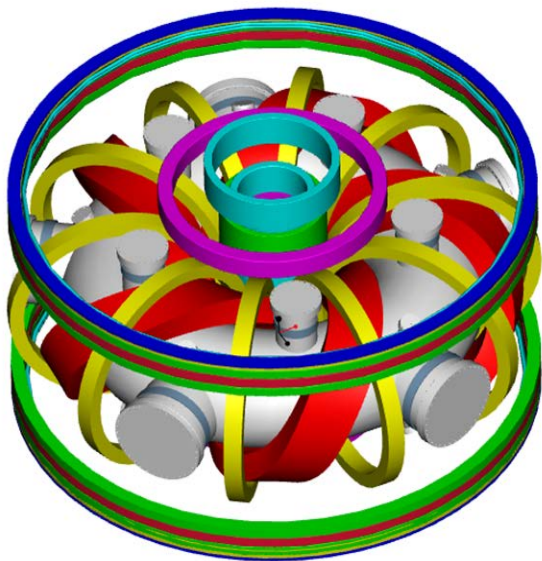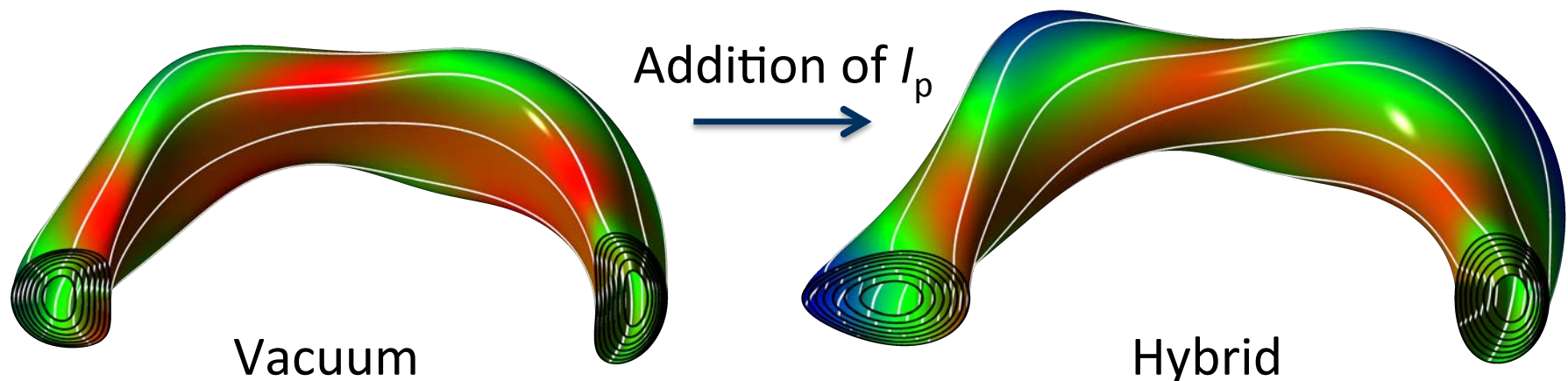
Outline

- Compact Toroidal Hybrid

- **3D equilibrium reconstruction**

- Disruption avoidance:

    1. Vertically unstable plasmas

    2. Density limit disruptions

    3. Low-q disruptions

- Summary and conclusions

3D equilibrium reconstruction with V3FIT is an essential tool for interpreting CTH plasmas

- CTH plasmas are not axisymmetric
  - Can not use EFIT or other 2D equilibrium solvers based on Grad–Shafranov equation
- Unlike conventional low-β stellarators, CTH low-β equilibrium strongly modified by plasma current

Addition of I_p

Vacuum

Hybrid

V3FIT uses the VMEC equilibrium solver to reconstruct CTH equilbria

(J.D. Hanson et al., Nucl. Fusion, 2009)
(S.P. Hirshman et al., Comput. Phys. Commun. 1986)

- Find MHD equilibrium most consistent with data
  - Over 40 external magnetic diagnostics as input
    - Full and segmented Rogowski coils
    - Saddle coils
    - B_θ and B_r pickup coils
  - SXR inversion surface position
- Reconstructed parameters
  - Enclosed toroidal flux
    - Plasma shape
  - Plasma current profile
   - Rotational transform profile
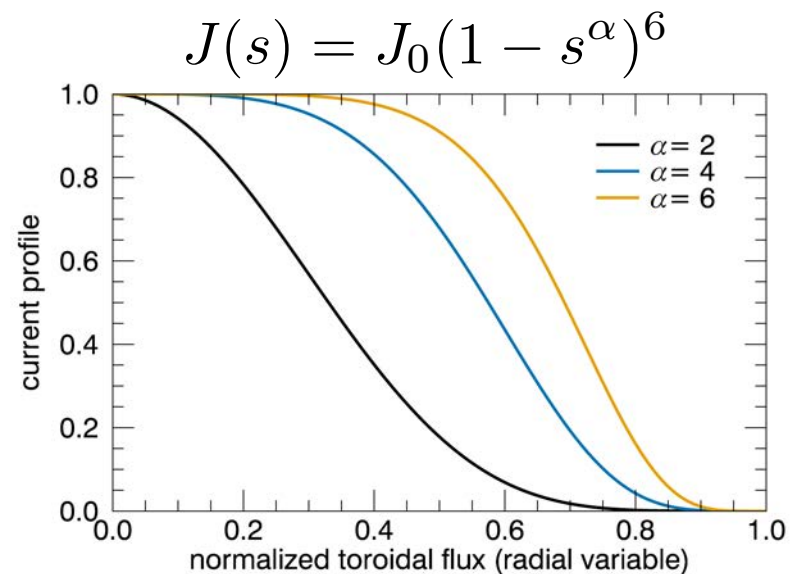
$$J(s) = J_0(1 - s^\alpha)^6$$

Outline

- Compact Toroidal Hybrid
- 3D equilibrium reconstruction
- Disruption avoidance:
  1. Vertically unstable plasmas
  2. Density limit disruptions
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CTH discharges naturally elongated and can be susceptible to vertical instability

- ECRH plasma I_p = 0 kA
  - Mean κ = 2.77
  - Fractional transform $f = \iota_{vac}(a)/\iota_{tot}(a) = 1$
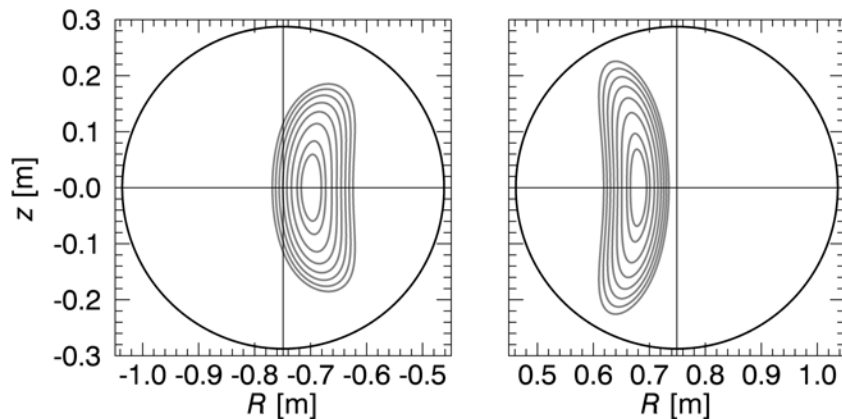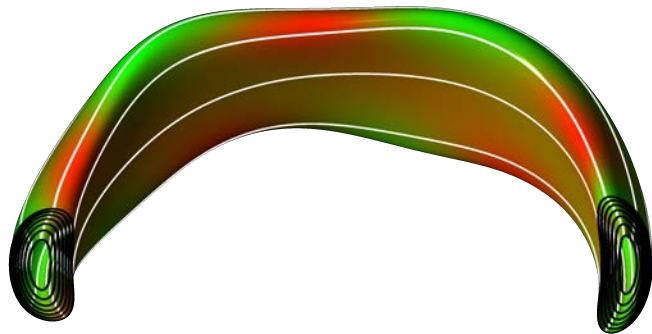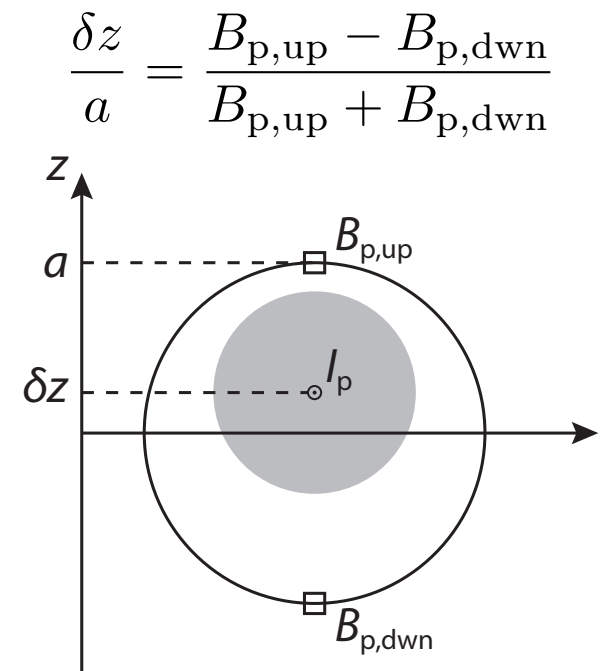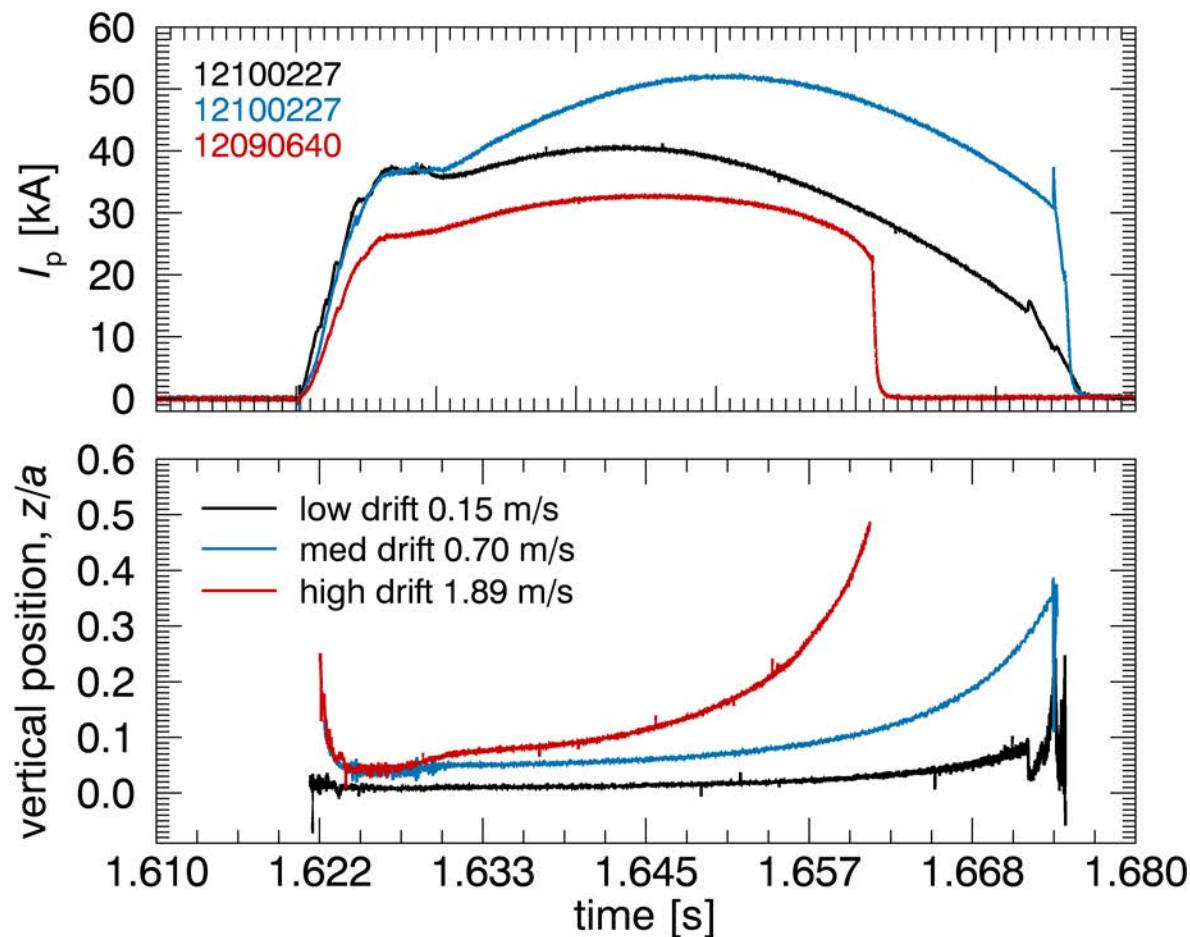
- At peak I_p = 75 kA
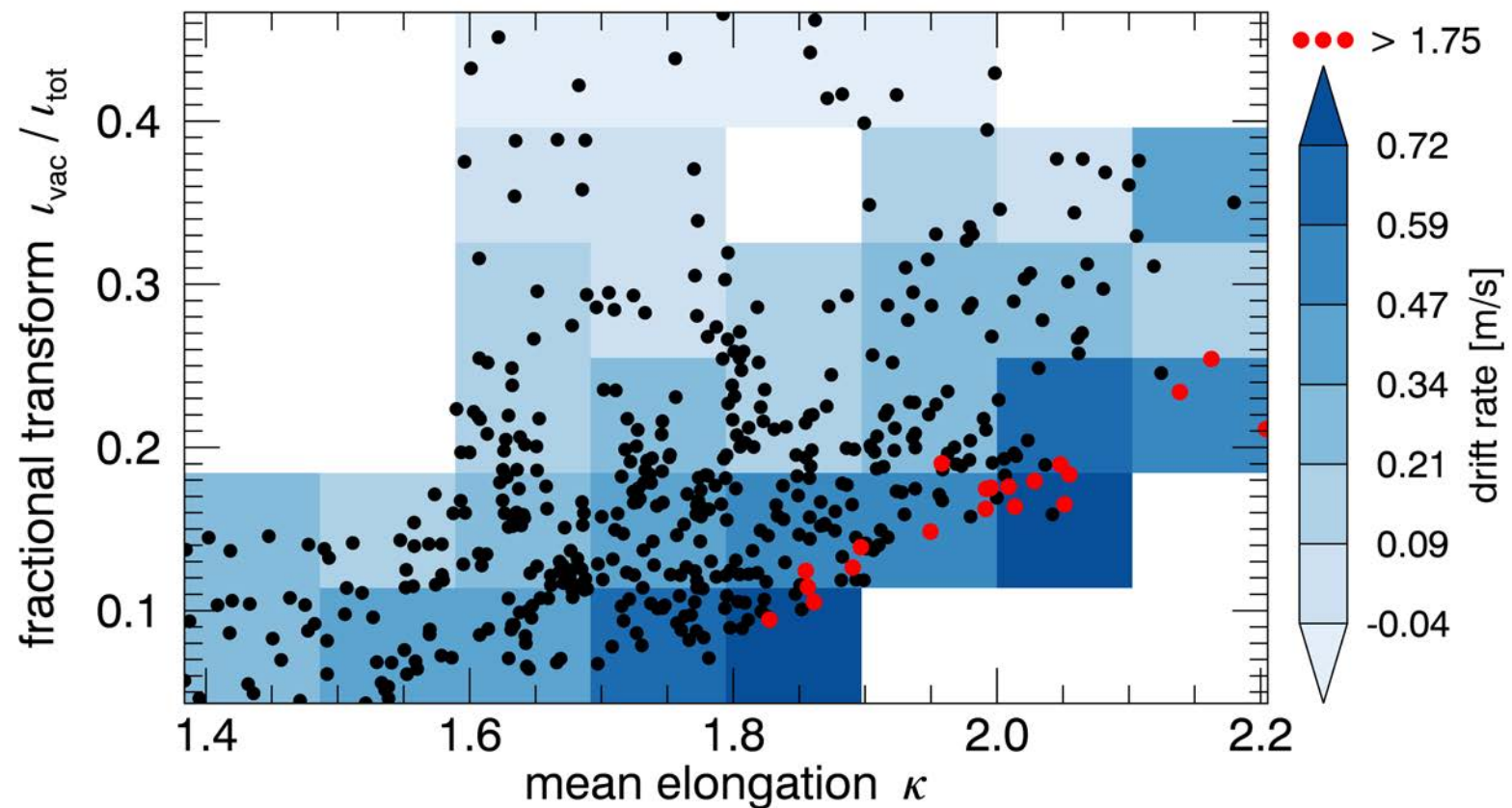 - Mean κ = 1.48
  - Fractional transform f = 0.0634
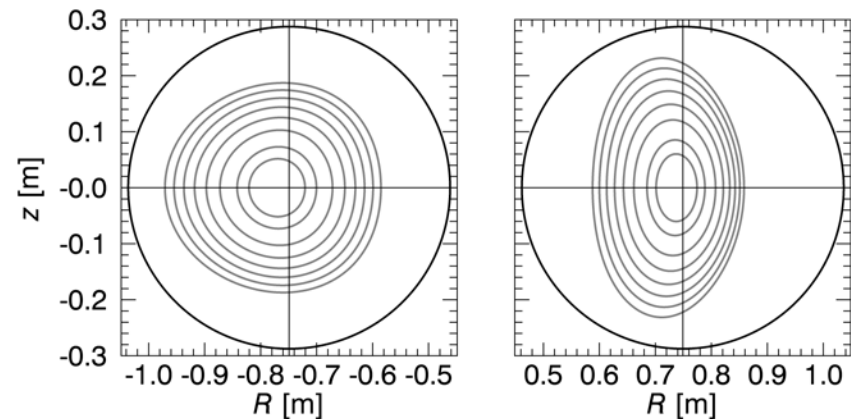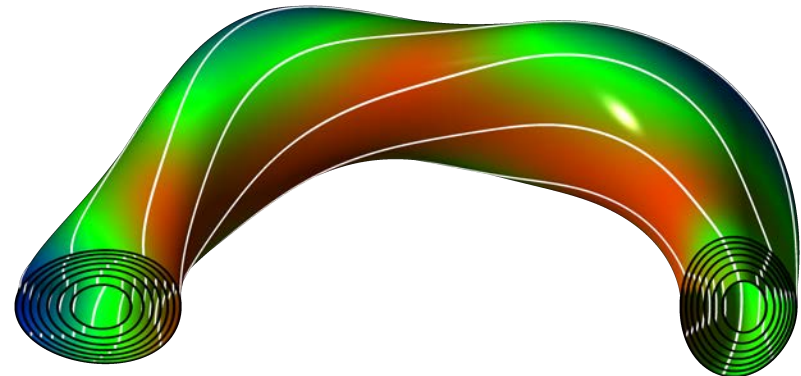
Elongated plasmas are measured to be vertically unstable

- Vertical position inferred from magnetic diagnostics

$$\frac{\delta z}{a} = \frac{B_{\mathrm{p,up}} - B_{\mathrm{p,dwn}}}{B_{\mathrm{p,up}} + B_{\mathrm{p,dwn}}}$$

# Plasmas with high elongation stabilized by addition of vacuum transform

(M.C. ArchMiller, et al., Phys. Plasmas 2014)

Qualitative agreement with analytic criterion for vertical stability

- Energy principle used to derive fraction of vacuum transform needed to stabilize vertical mode in a current-carrying stellarator (G.Y. Fu, Phys. Plasmas, 2000)

- $f \equiv \dfrac{\iota_{\mathrm{vac}}(a)}{\iota_{\mathrm{tot}}(a)} \geq \dfrac{\kappa^2 - \kappa}{\kappa^2 + 1}$

- Large aspect ratio, low-β stellarator

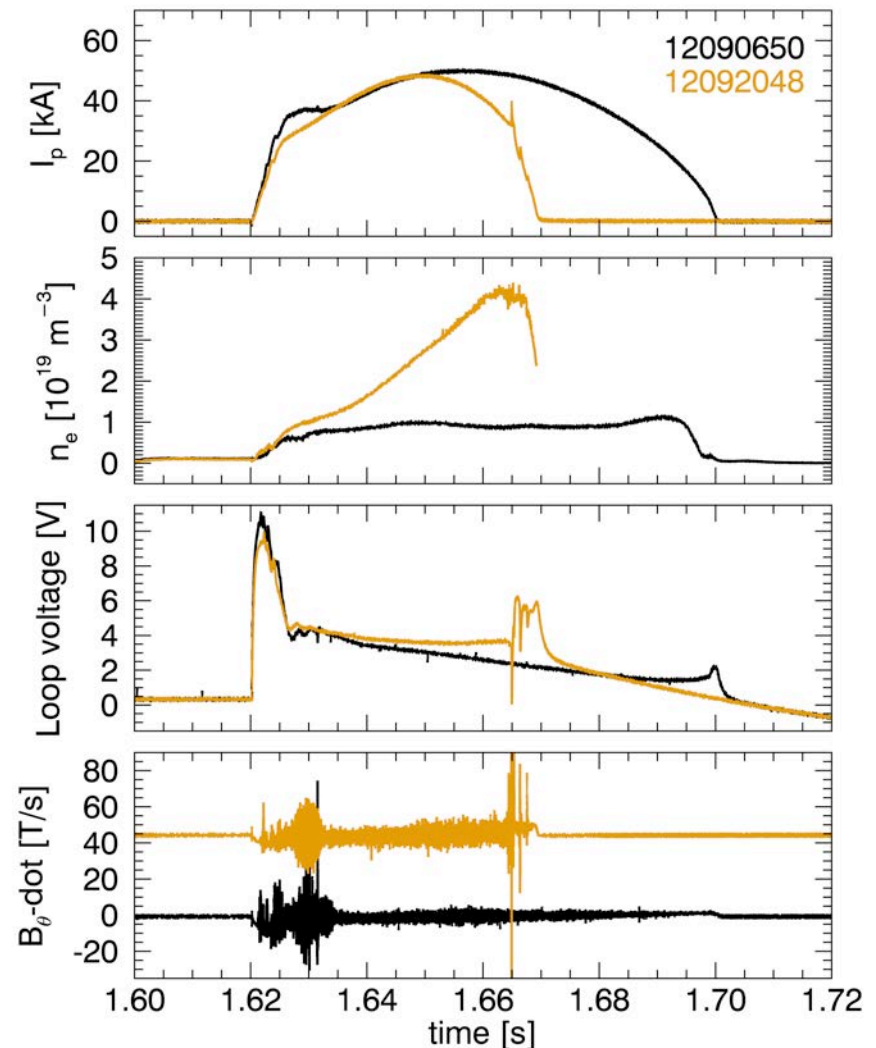- Uniform profiles of current density and vacuum rotational transform
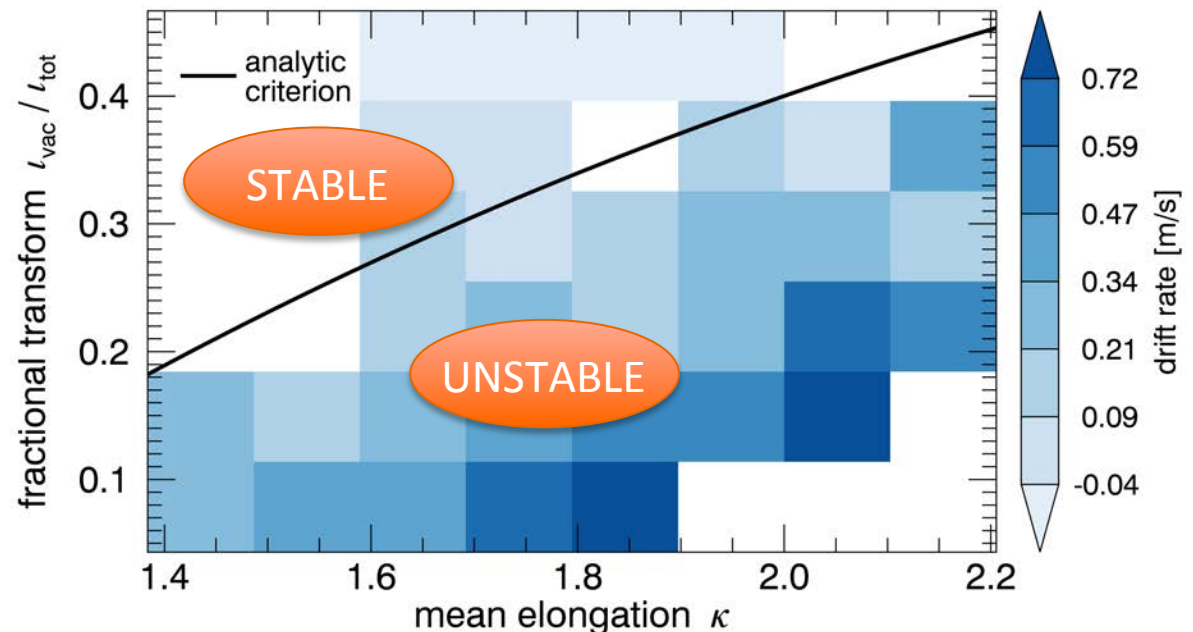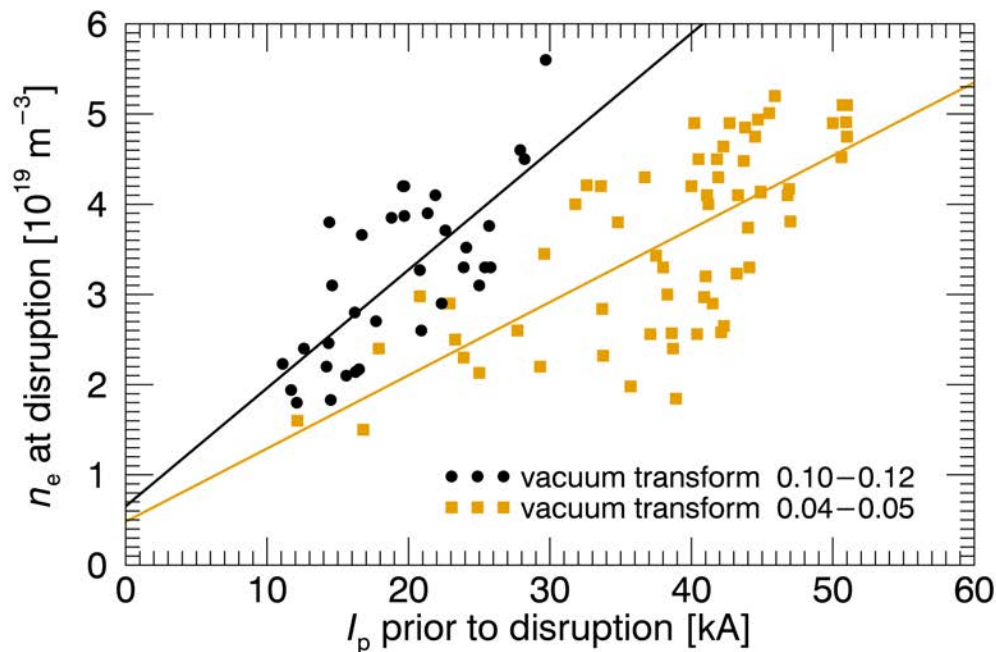
Outline

- Compact Toroidal Hybrid
- 3D equilibrium reconstruction
- Disruption avoidance and mitigation:
  1. Vertically unstable plasmas
  2. Density limit disruptions
  3. Low $q(a)$ disruptions
- Summary and conclusions

Density limit disruptions triggered by ramping density with edge fueling

- **Discharges with similar low transform t_{vac} = 0.05**
- **CTH terminations similar to tokamak disruptions:**
  - Negative loop voltage spike
  - Current spike followed by rapid decay
  - Strong coherent MHD precursor
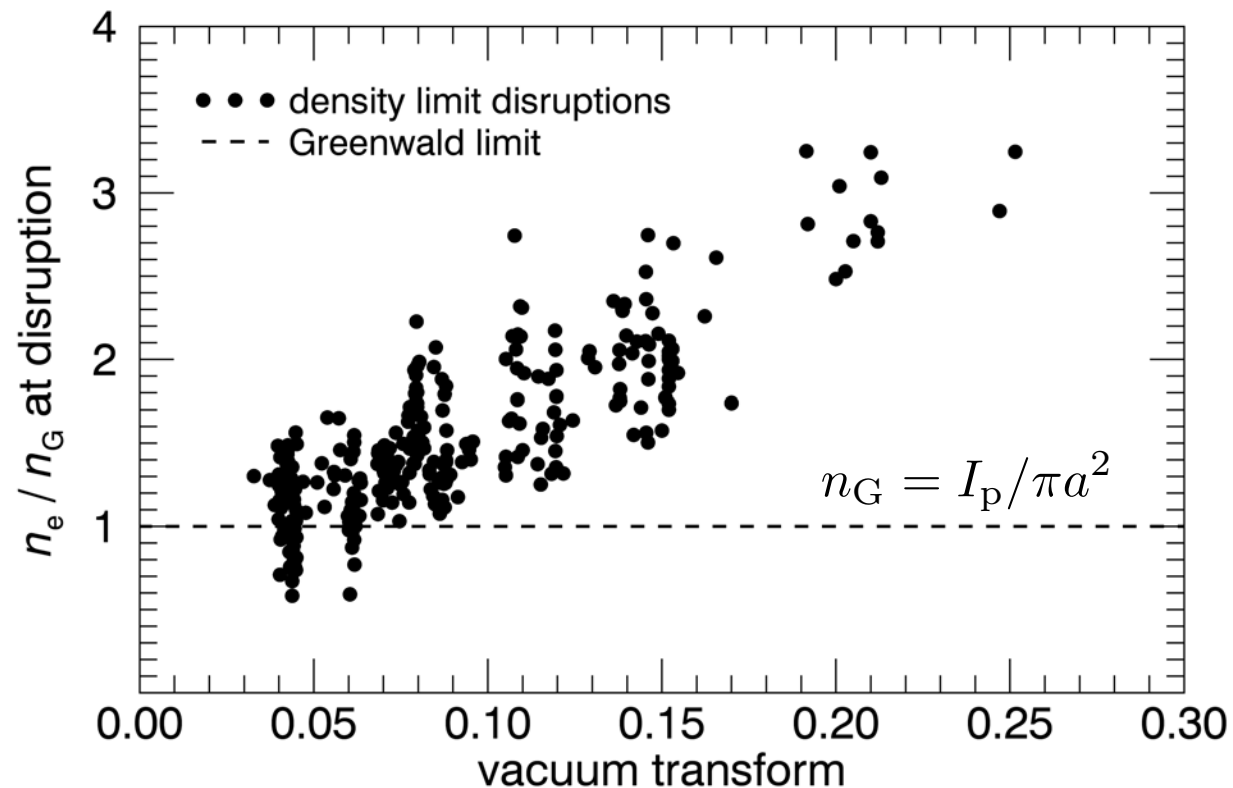- **Disruption preceded by rotating *m/n* = 2/1 tearing mode**

Density at disruption scales with the plasma current and vacuum transform

- Follows trend of Greenwald limiting behavior:
  - $n_{\mathrm{G}} = I_{\mathrm{p}}/\pi a^2$

- Additional dependence on applied level of vacuum transform

(M. Greenwald et al., Nucl. Fusion, 1988)

# Density at disruption exceeds Greenwald limit as vacuum transform is increased

The plot shows n_e / n_G at disruption versus vacuum transform, with data points labeled "density limit disruptions" and a dashed line for "Greenwald limit". The equation shown is:

$$n_G = I_p / \pi a^2$$

- No observed threshold on vacuum transform to avoid density limit disruptions

Outline

- Compact Toroidal Hybrid
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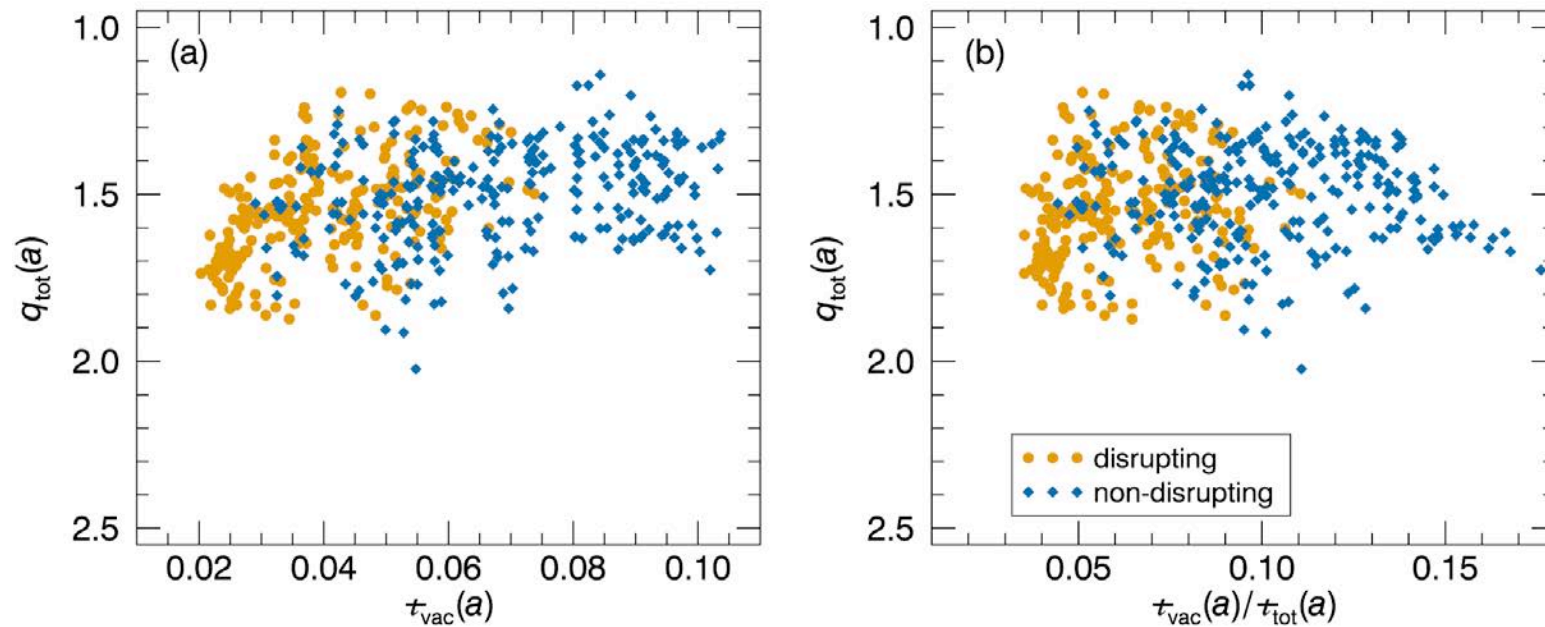# High current plasmas disrupt with $q(a)$ below 2 and low vacuum transform
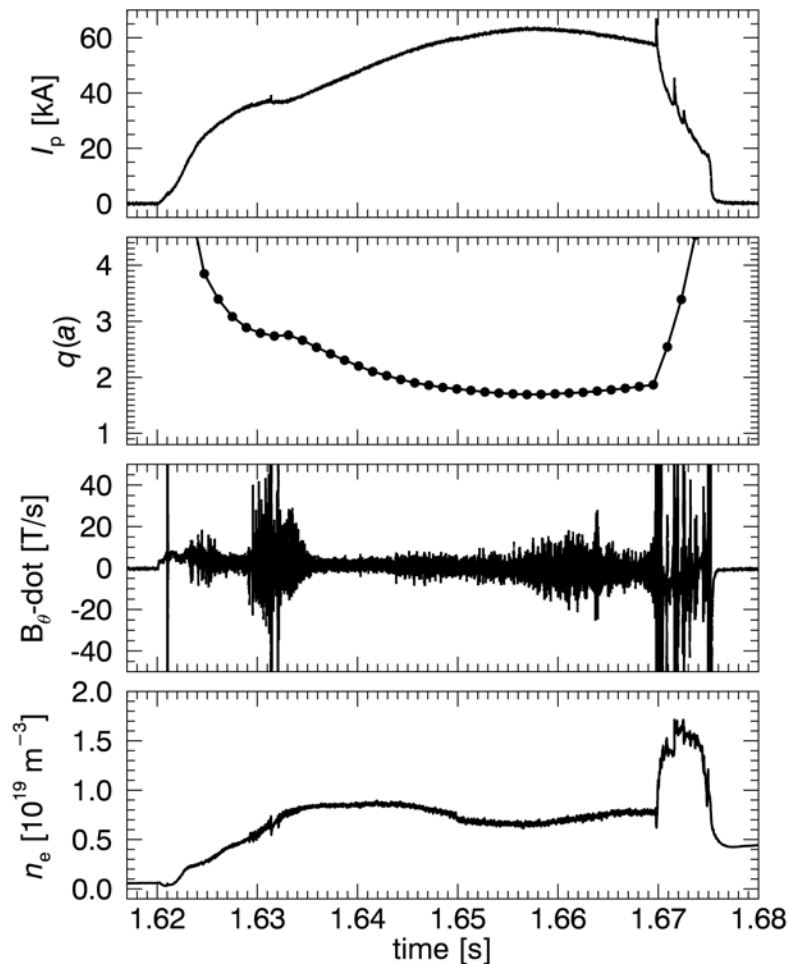
- Example with $t_{vac} = 0.02$ ($q_{vac} = 50$)

- Disruption does not occur on initial crossing of $q(a) = 2$

- Density kept low and roughly constant

Low-*q* disruptions cease to occur if vacuum transform raised above ~ 0.07
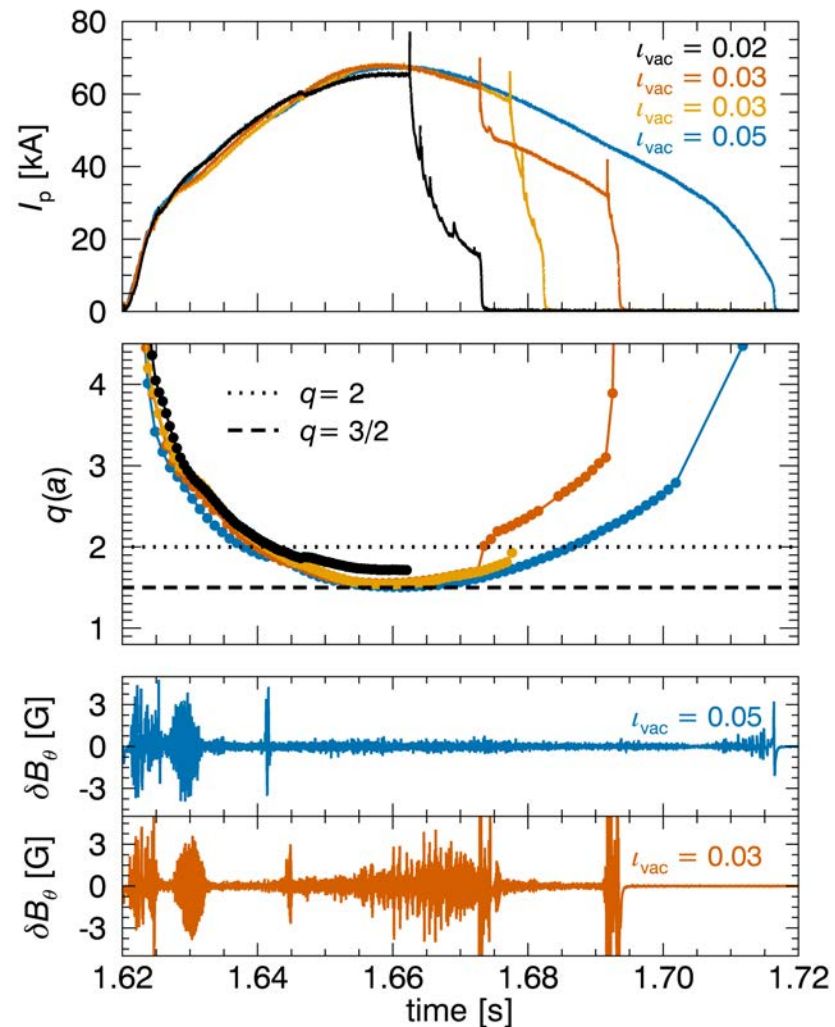
Low-*q* disruptions cease to occur if vacuum transform raised above ~ 0.07

- Possible explanation:
  - Applied t_{vac} shifts 3/2 resonance outward
  - Current profile is less steep -> stabilizes 3/2 tearing mode
  - Invoked for stabilizing 2/1 tearing mode in W7-A

Summary and conclusions

- Vertical stability of elongated plasmas improved by stellarator transform
  - Qualitative agreement with analytic theory

- Disruptive density limit exceeds Greenwald limit as vacuum transform is increased
  - Threshold for avoidance not observed

- Low-q disruptions cease to occur if vacuum transform raised above ~ 0.07 ($q_{vac}(a)$ ~ 14)
  - $m = 2$, $n = 1$ mode not implicated in disruption

Backup slides

Disruption precursor fluctuations indicate internal tearing mode

- MHD modulates density and SXR emission
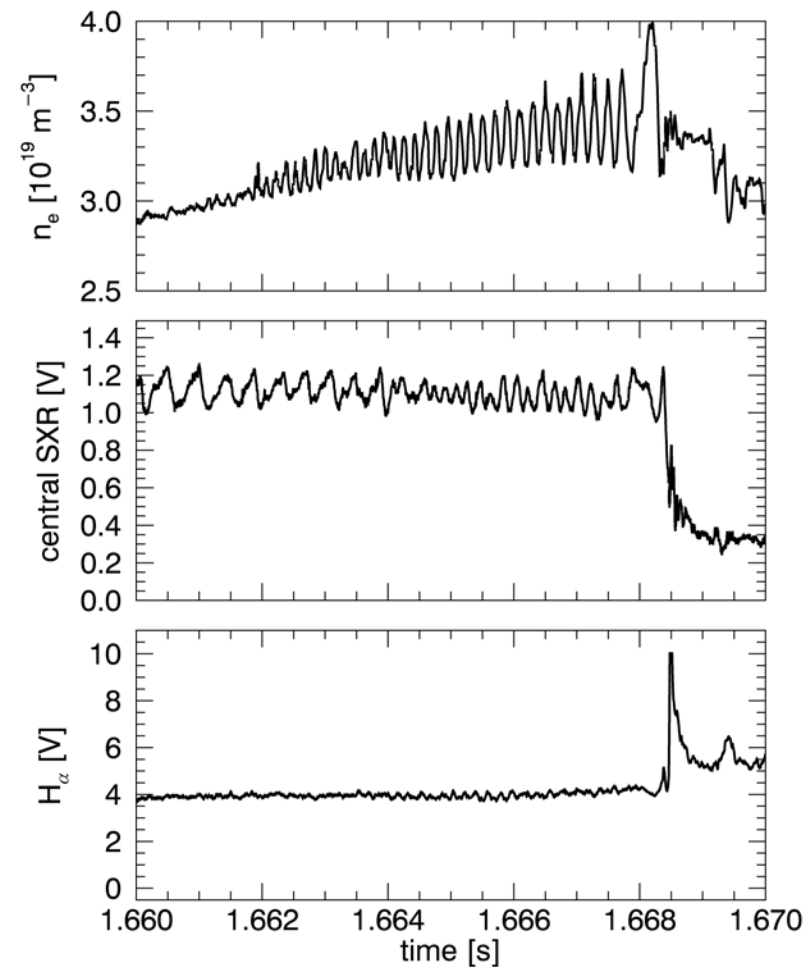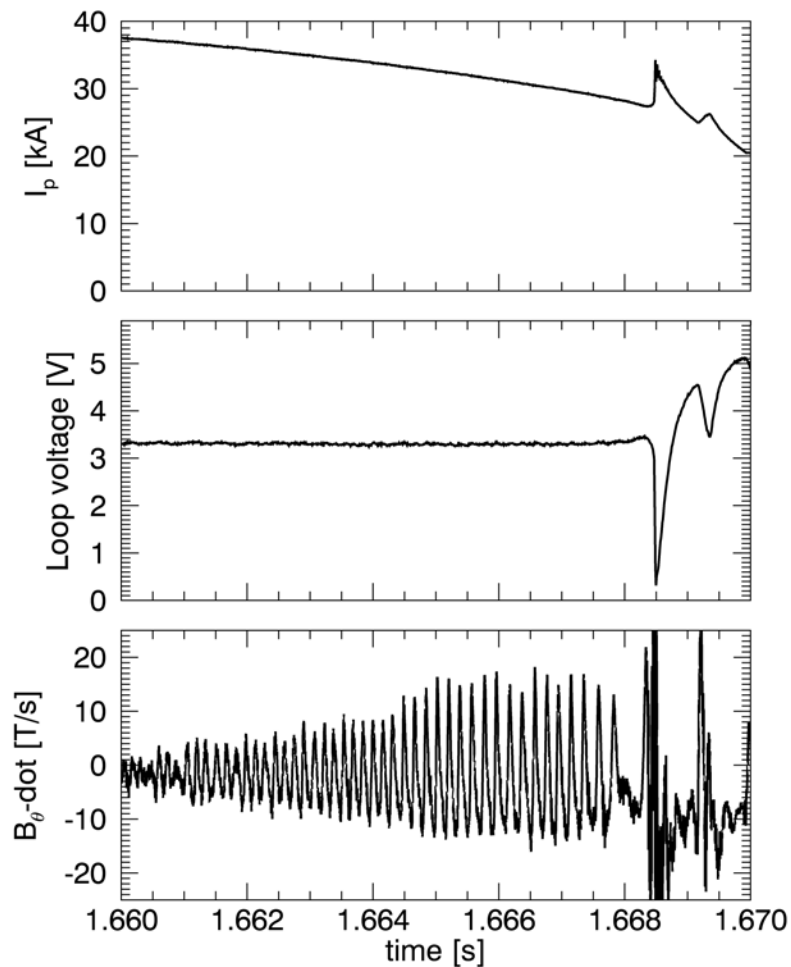
# Disruption preceded by rotating $m/n = 2/1$ tearing mode that locks
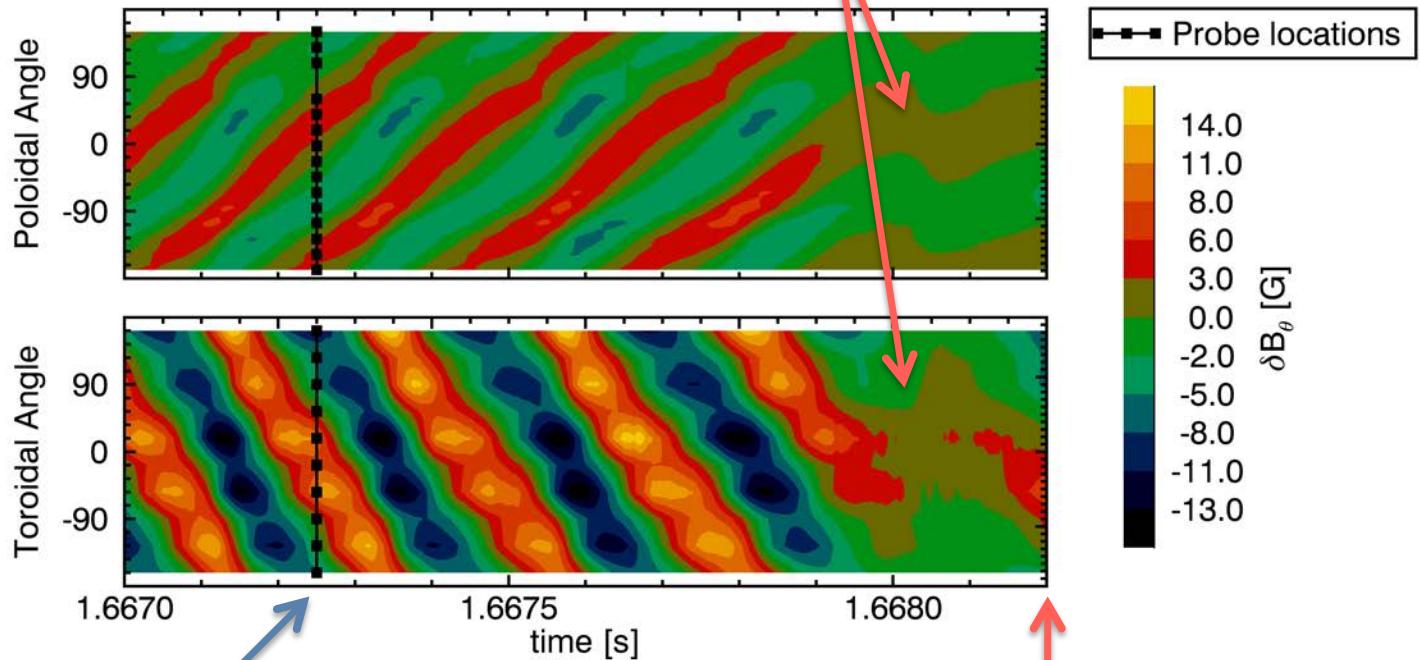
Density at disruption observed to be independent of plasma current evolution

- Discharges with similar transform $t_{vac} = 0.07$

- Different programmed loop voltage

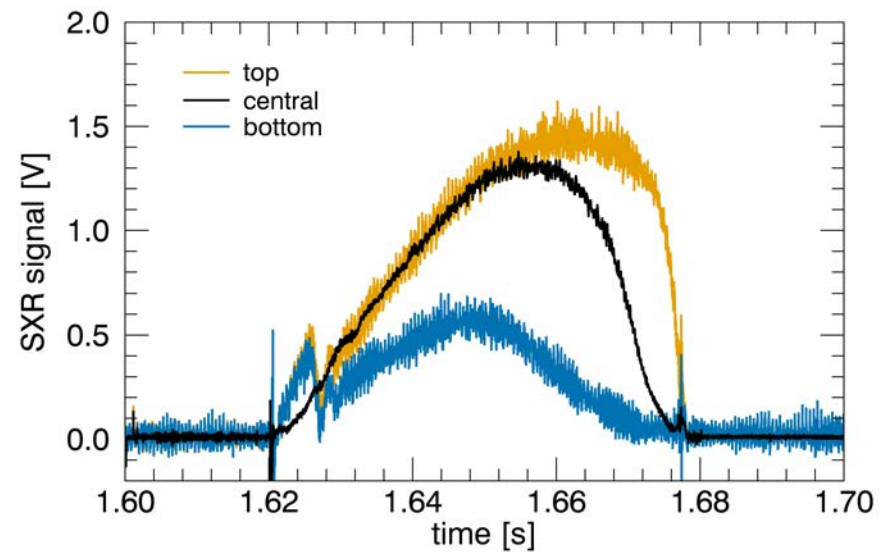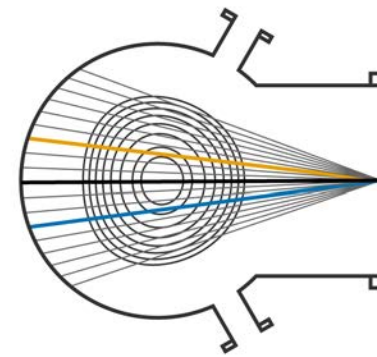- Disruption occurrence correlates with plasma current and density as in tokamaks
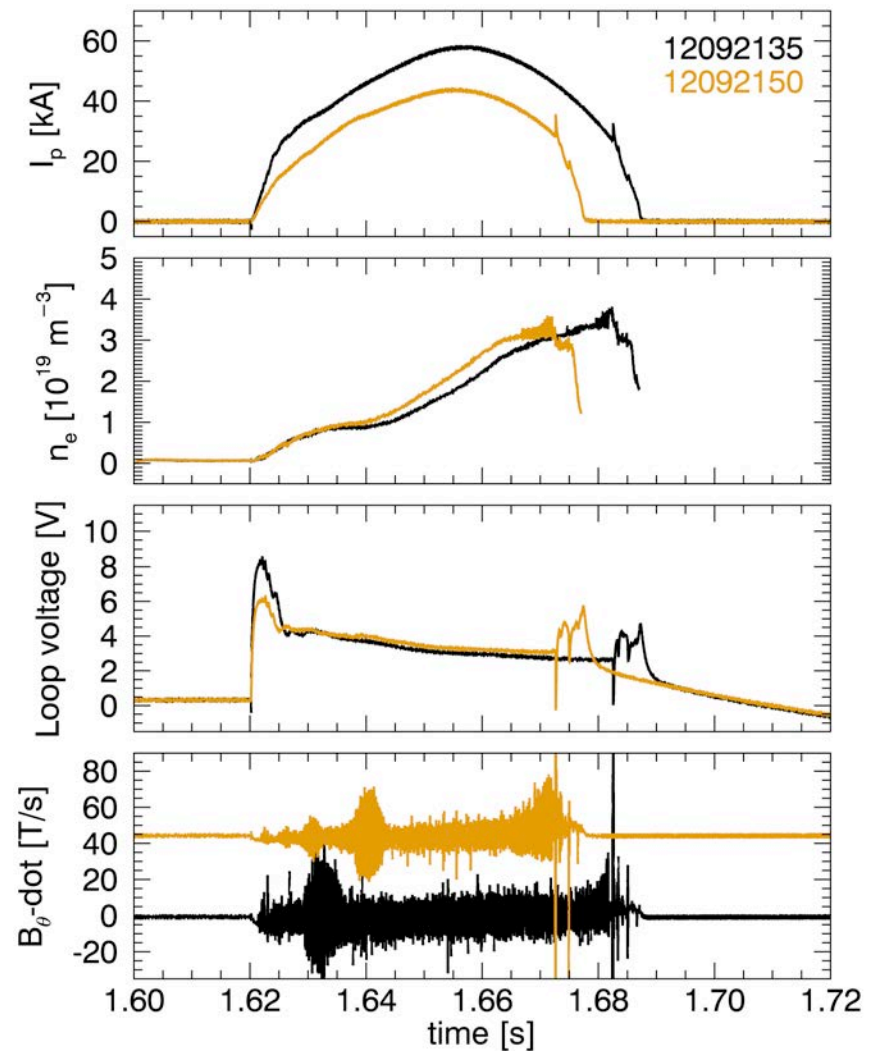
Vertical motion is also detected by interferometry and SXR cameras
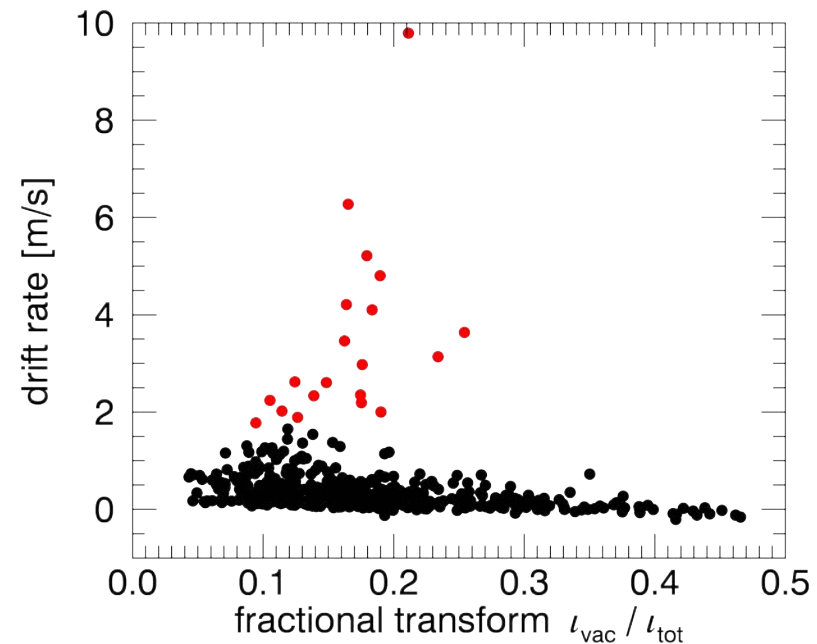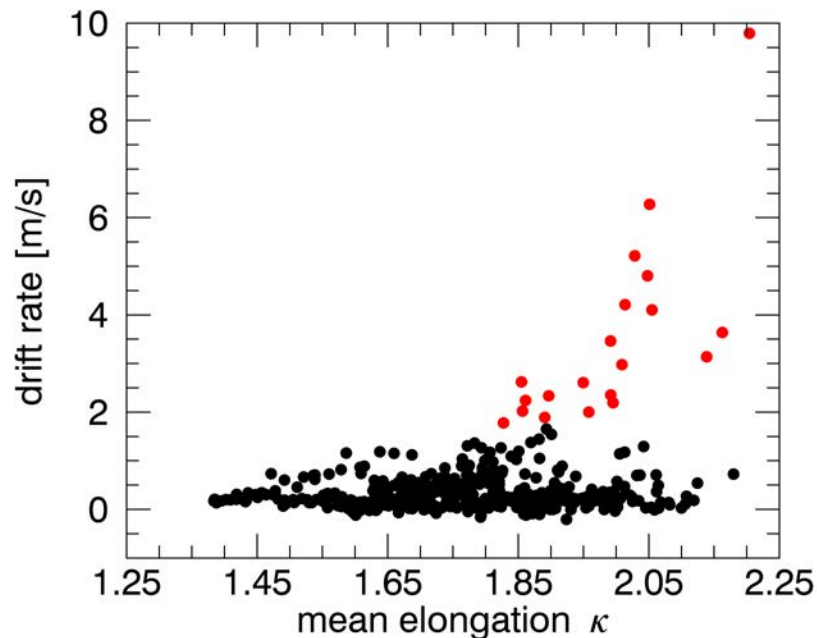

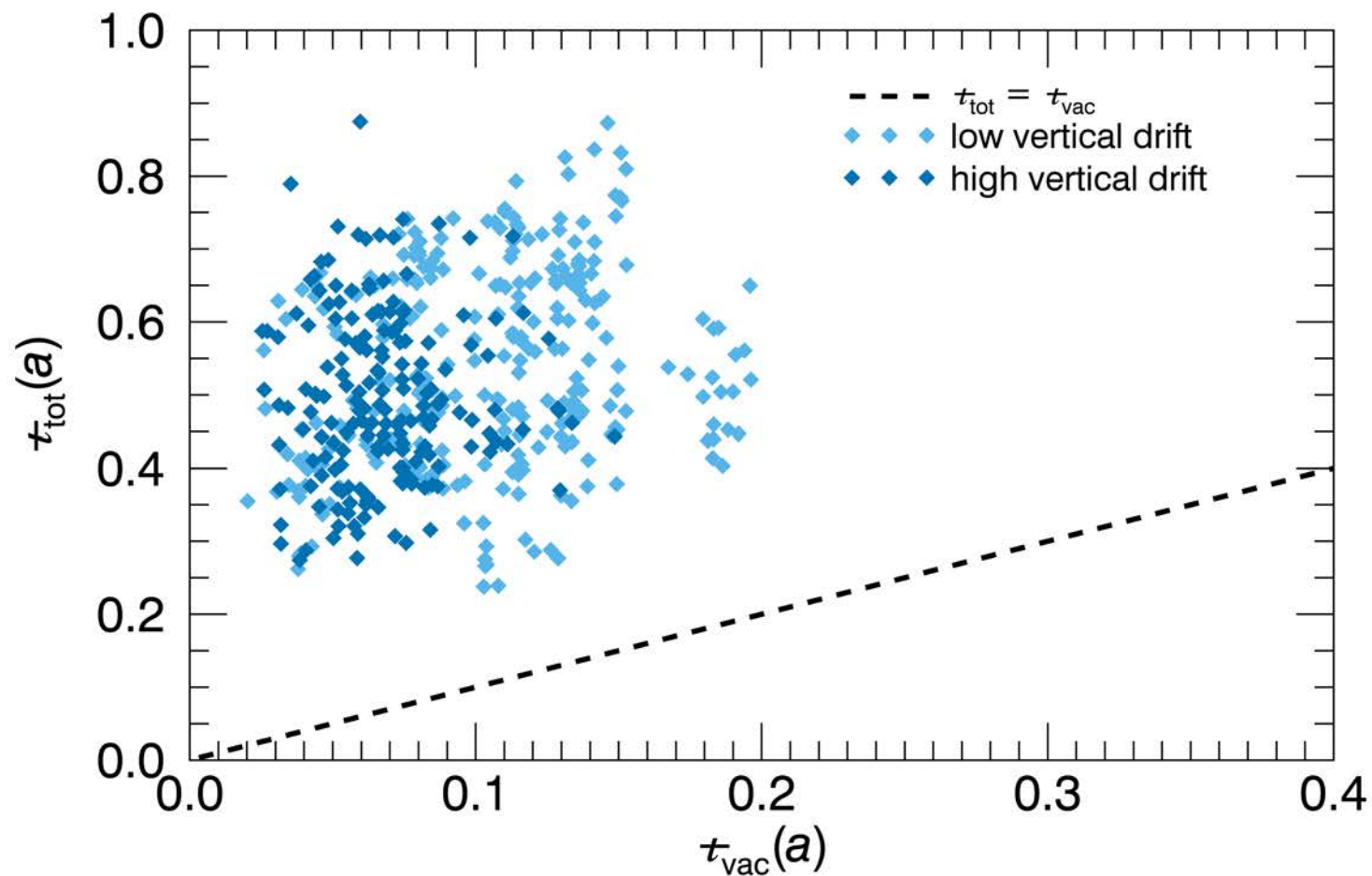1mm wave interferometer
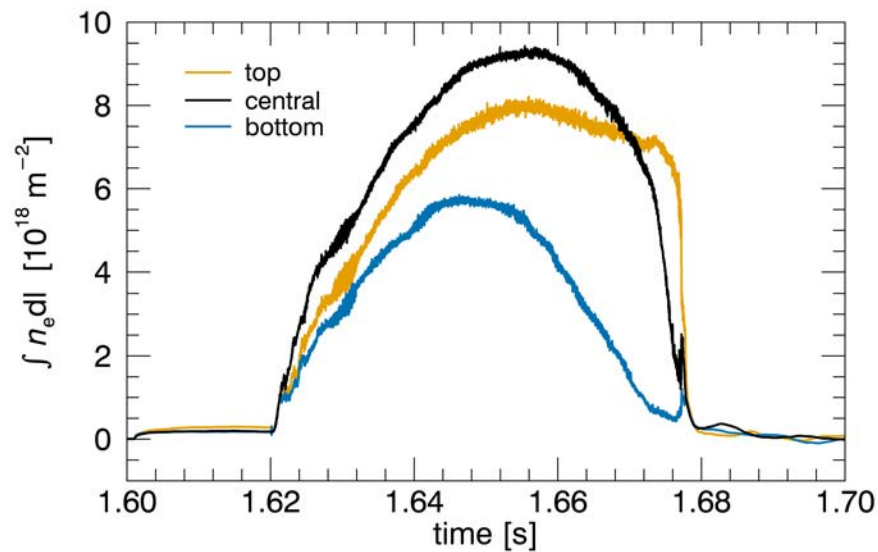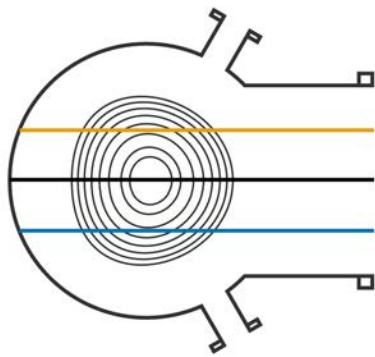
SXR pinhole camera

Discharges exhibit faster drift at high elongation and low fractional transform
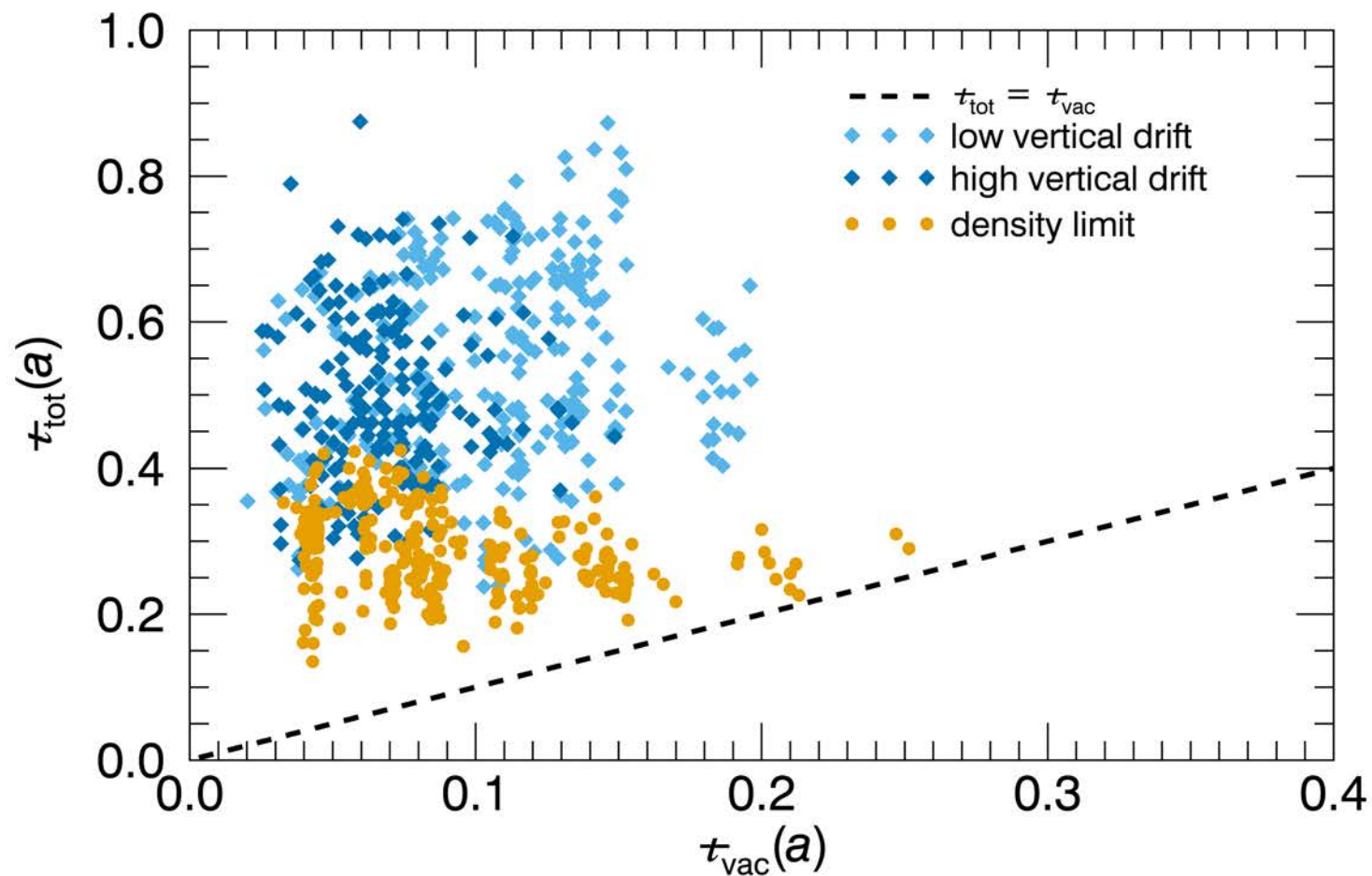
- Large ensemble of discharges with varied elongation and fractional transform

Review of disruption observations

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Review of disruption observations