The Compact Toroidal Hybrid
A university scale fusion experiment

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CTH Team and Collaborators

- CTH
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- Oak Ridge National Lab
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- DIII-D
- HSX
- W7-X

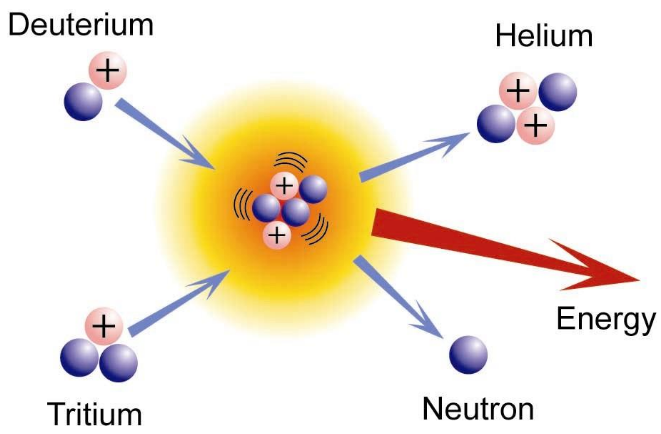
U.S. DEPARTMENT OF ENERGY

Office of Science
U.S. Department of Energy

Outline

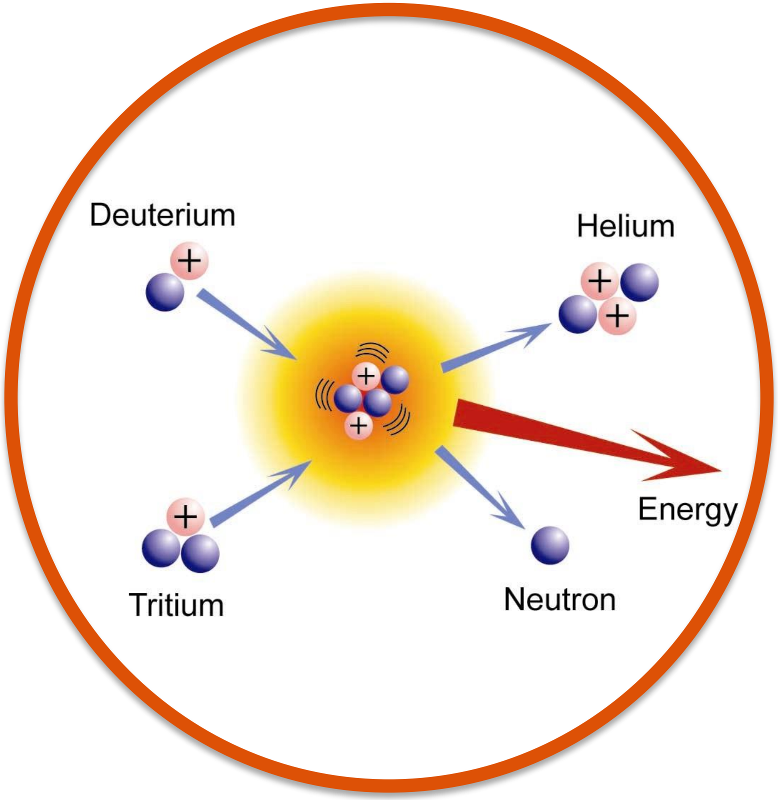
- Fusion Energy and Magnetic Confinement
- Motivation
  - Disruptions
  - Mitigation
- CTH
  - Hardware
  - Operation
- Disruption Studies
  - Vertical Displacement
  - Density Driven
  - Low q
- Future work

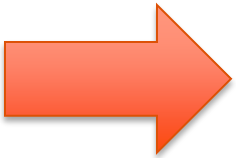
What is fusion energy?

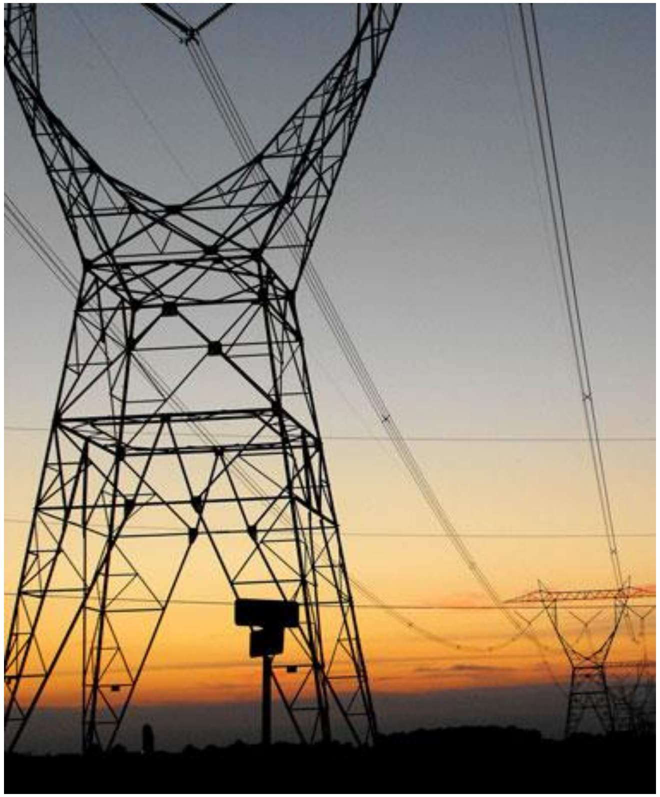


- Nuclear process combining light nuclei
- Difference in binding energy released
- Must overcome Coulomb force
- Need a combination of:
  - Temperature
  - Density
  - Time

The goal is to harness fusion energy to produce electricity

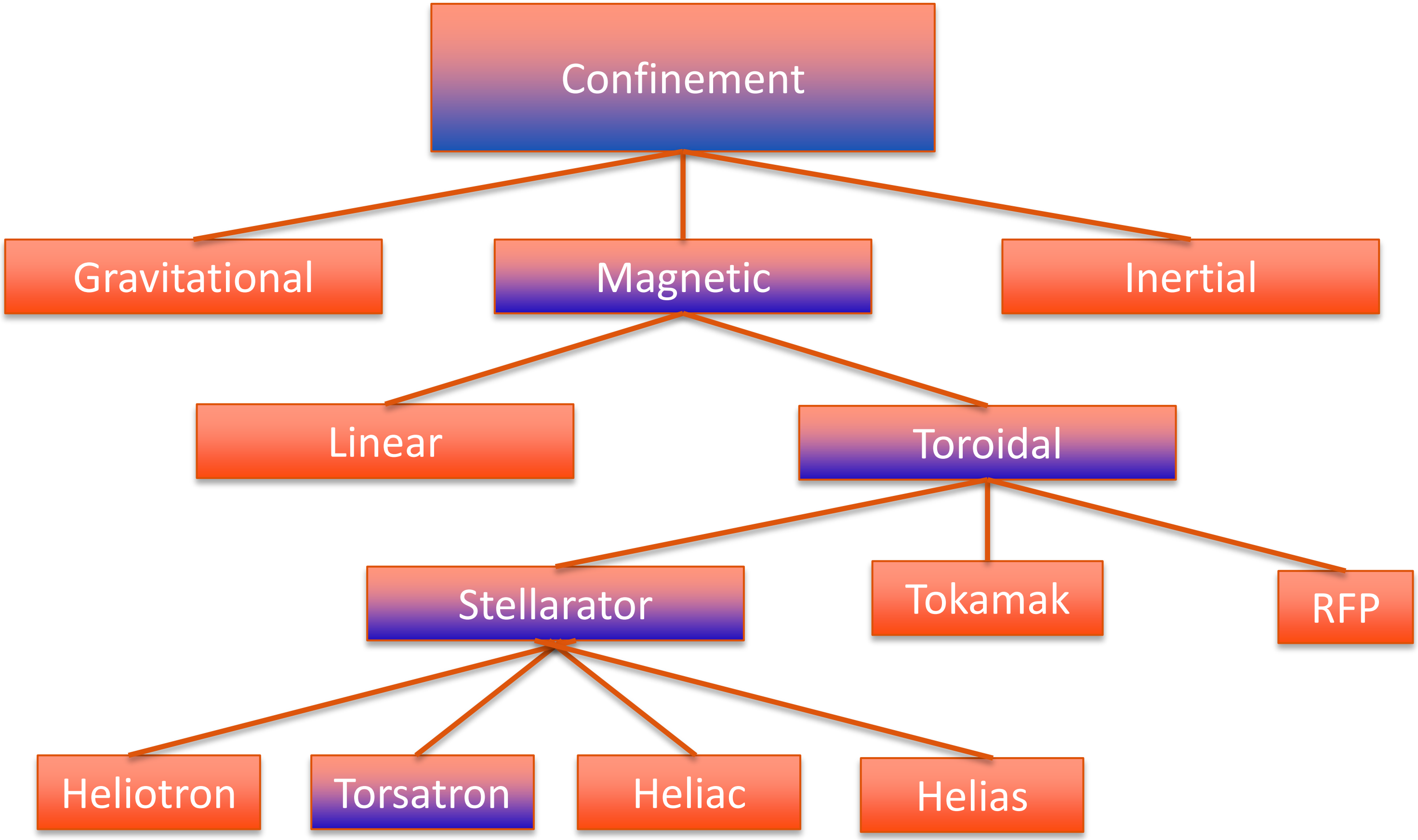






Confinement Device

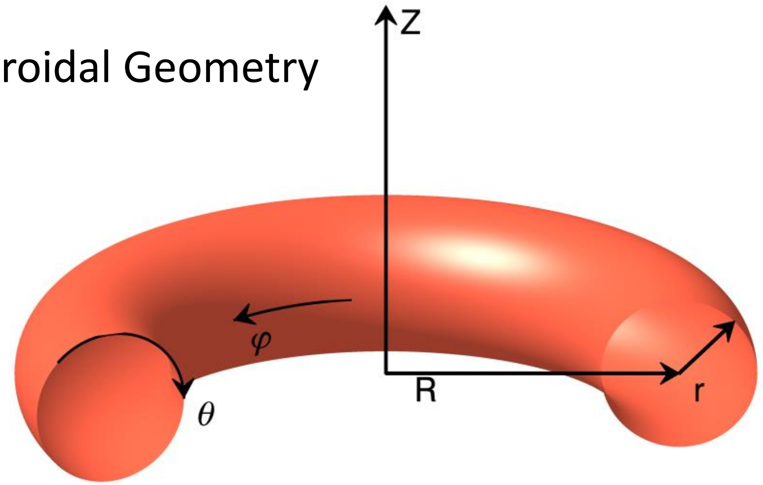
Plasma Confinement Schemes



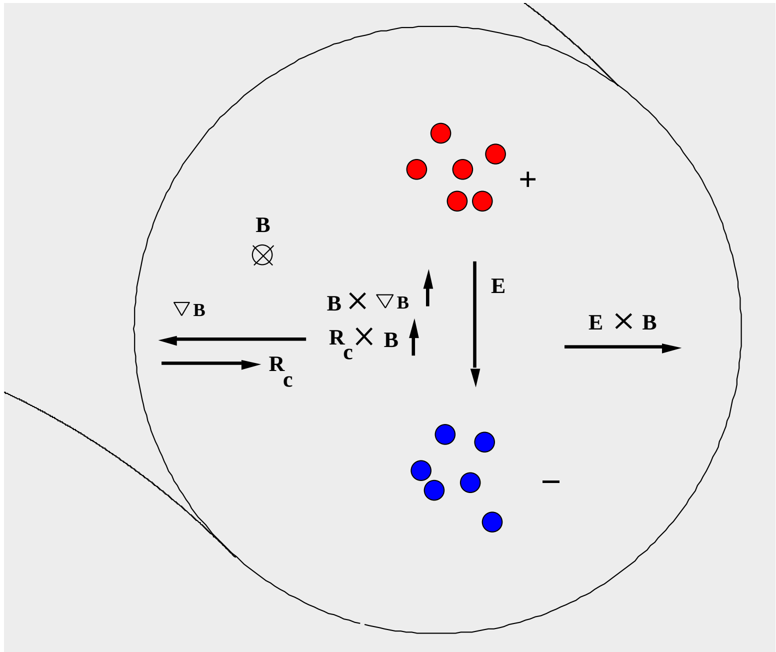
Helical magnetic fields are required for confinement in toroidal devices

- A purely toroidal field will not confine a plasma.
  - ∇B and curvature drifts polarize the plasma
  - $\boldsymbol{E} \times \boldsymbol{B}$ pushes plasma out

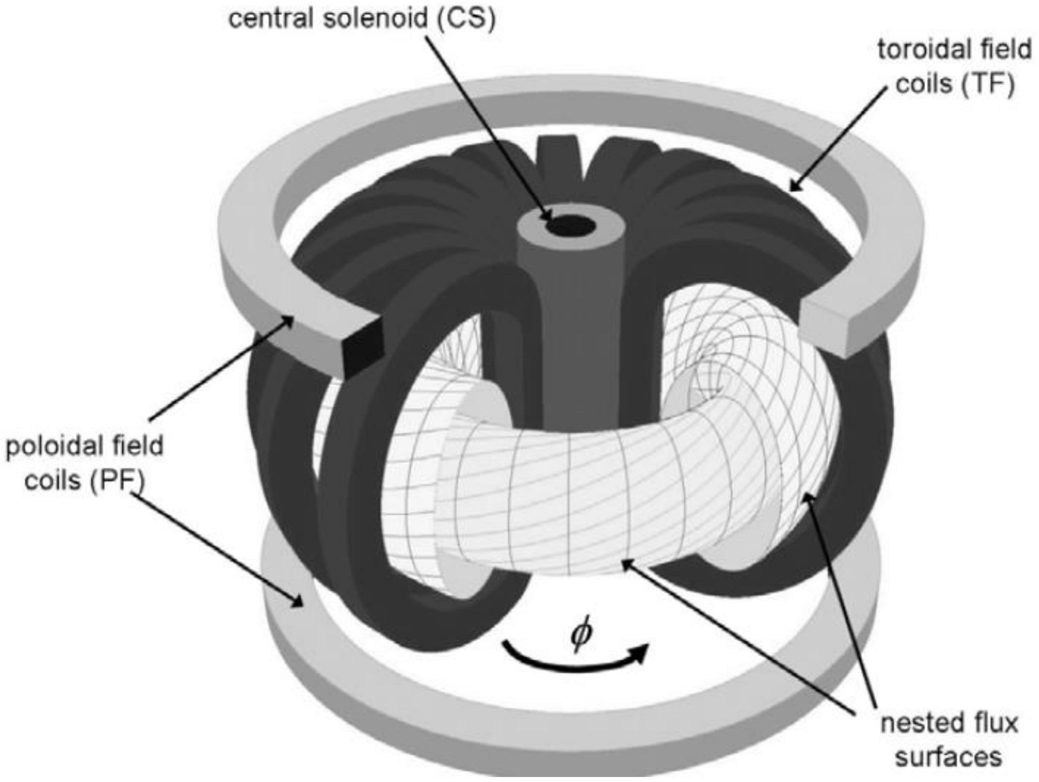
Toroidal Geometry

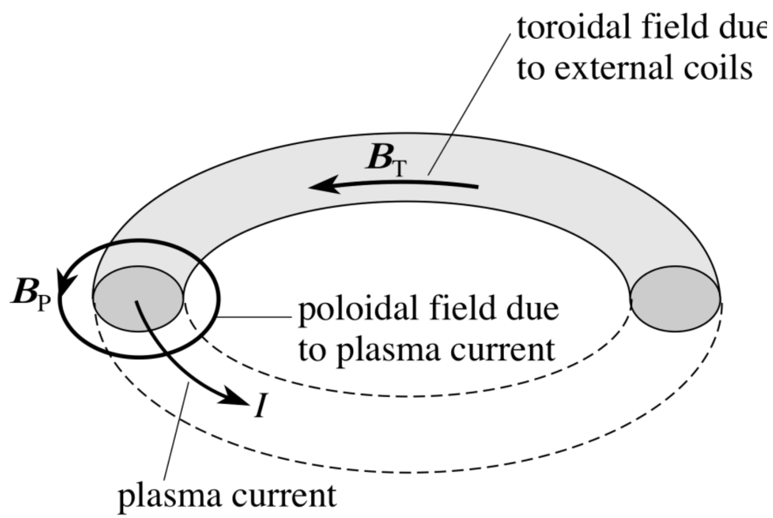


toroidal angle – φ
poloidal angle – θ



Tokamaks use a plasma current to create the helical magnetic field

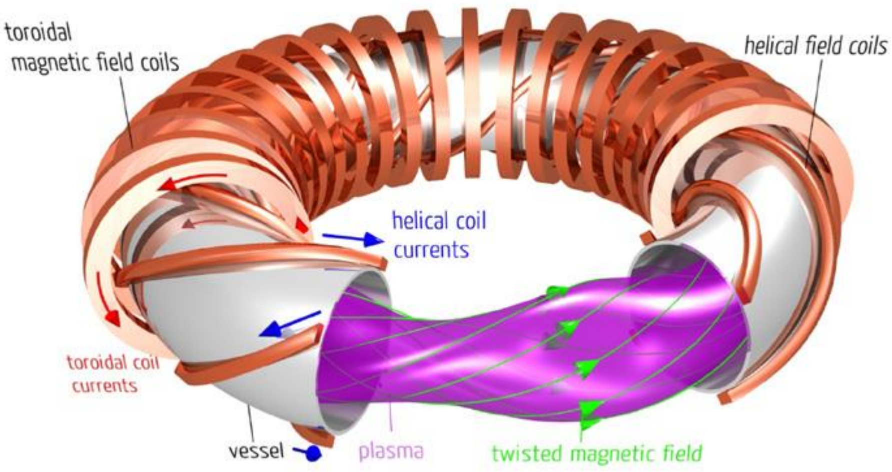


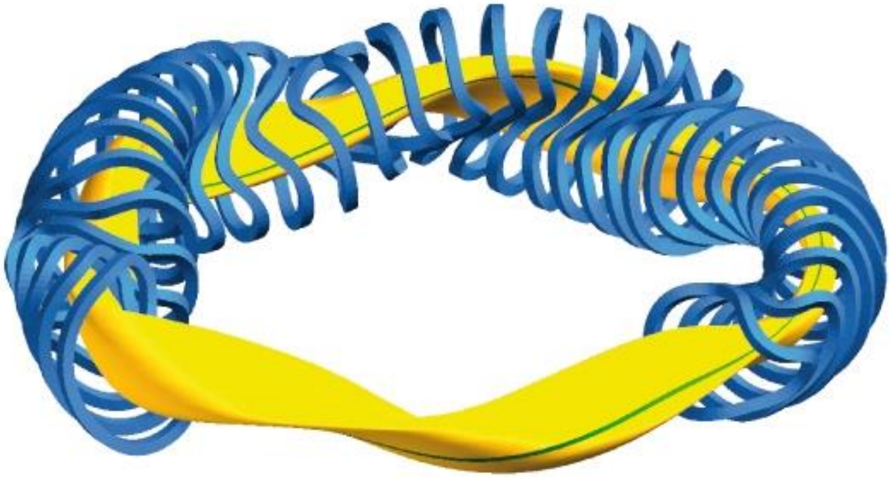


Stellarators create helical fields with external coils

Classic Stellarator
(a heliotron)

Modern Stellarator – W7-X
(a helias)



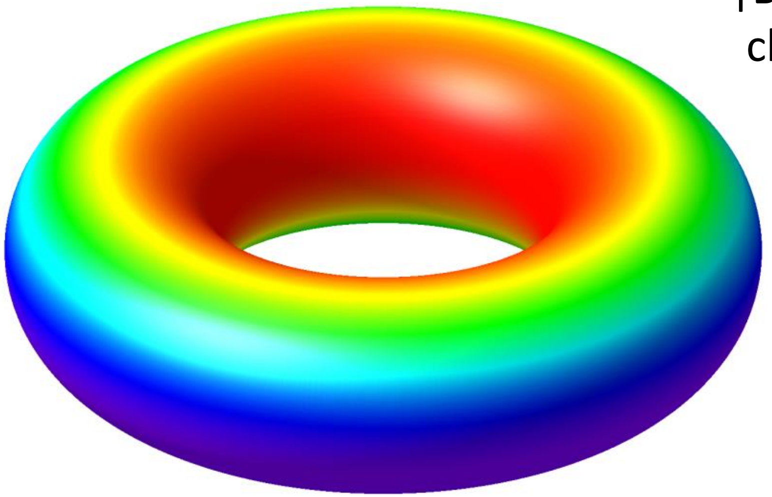


Toroidal field coils
Continuous helical field coils

Modular coils

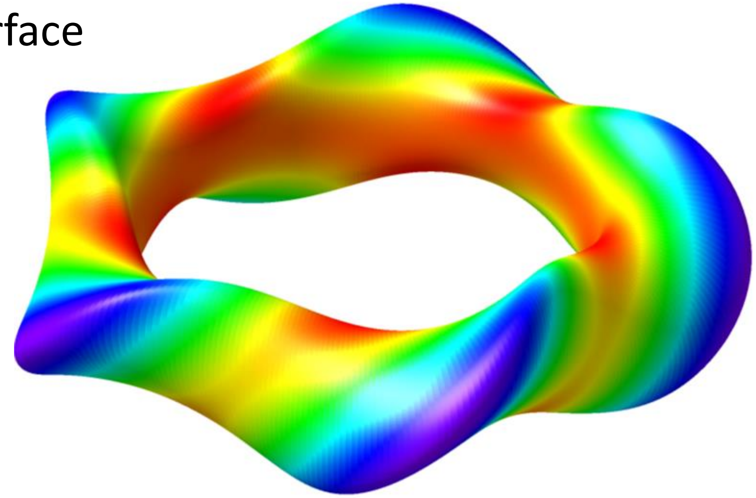
Differences between a tokamak and a stellarator

Tokamak



Stellarator

|B| contours on last closed flux surface



- Axisymmetric configuration
- MHD equilibrium requires externally driven toroidal plasma current
- Current driven instabilities lead to disruptions

- Non-axisymmetric configuration
- MHD equilibrium obtained with externally applied magnetic fields
- Current free - not susceptible to disruptions

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Disruption avoidance and mitigation is essential for future tokamaks

- Disruptions are sudden losses of plasma confinement
- Result in large particle and heat flows on plasma facing components
- Major concern for ITER operation
- Major focus of the US tokamak program
  - Predict
  - Avoid
  - Mitigate

Disruption in the Alcator C-mod tokamak

disruption

https://www.youtube.com/watch?v=06t3idDwdcQ

Present day tokamaks use 3D magnetic fields to improve control and performance

- Small amounts of 3D fields are used for a variety of purposes on present day tokamaks with $B_{3D}/B_0 \sim 10^{-3}$
  - Resistive wall modes, ELM control, error field correction

- Disruptions do not routinely occur in (net) current free stellarators

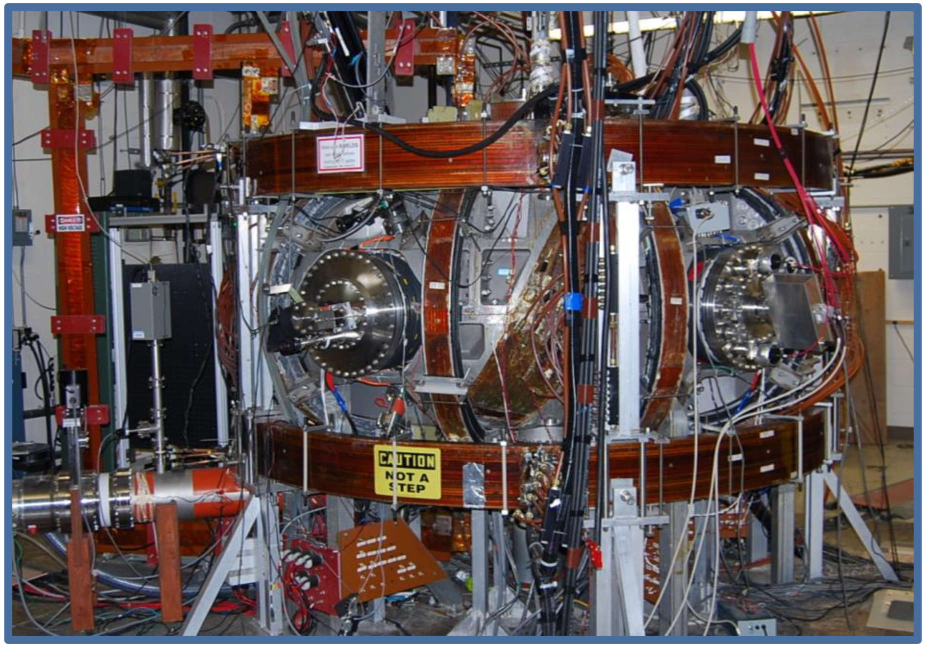
- CTH experiments seek to study the question:

  What is the effect of higher levels of 3D magnetic shaping, $B_{3D}/B_0 \sim 10\%$,

  on tokamak-like instabilities and disruptions?

The Compact Toroidal Hybrid (CTH) is designed to study the effect of 3D shaping on the MHD stability of a current carrying stellarator

- Torsatron device – closed magnetic flux surfaces provided by external coils
- Hybrid – plasma current is driven within the 3D equilibrium of a stellarator plasma
- CTH can vary the relative amount of externally applied transform to that generated by internal plasma current



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The vacuum vessel is a circularly symmetric torus with port extensions for diagnostic access

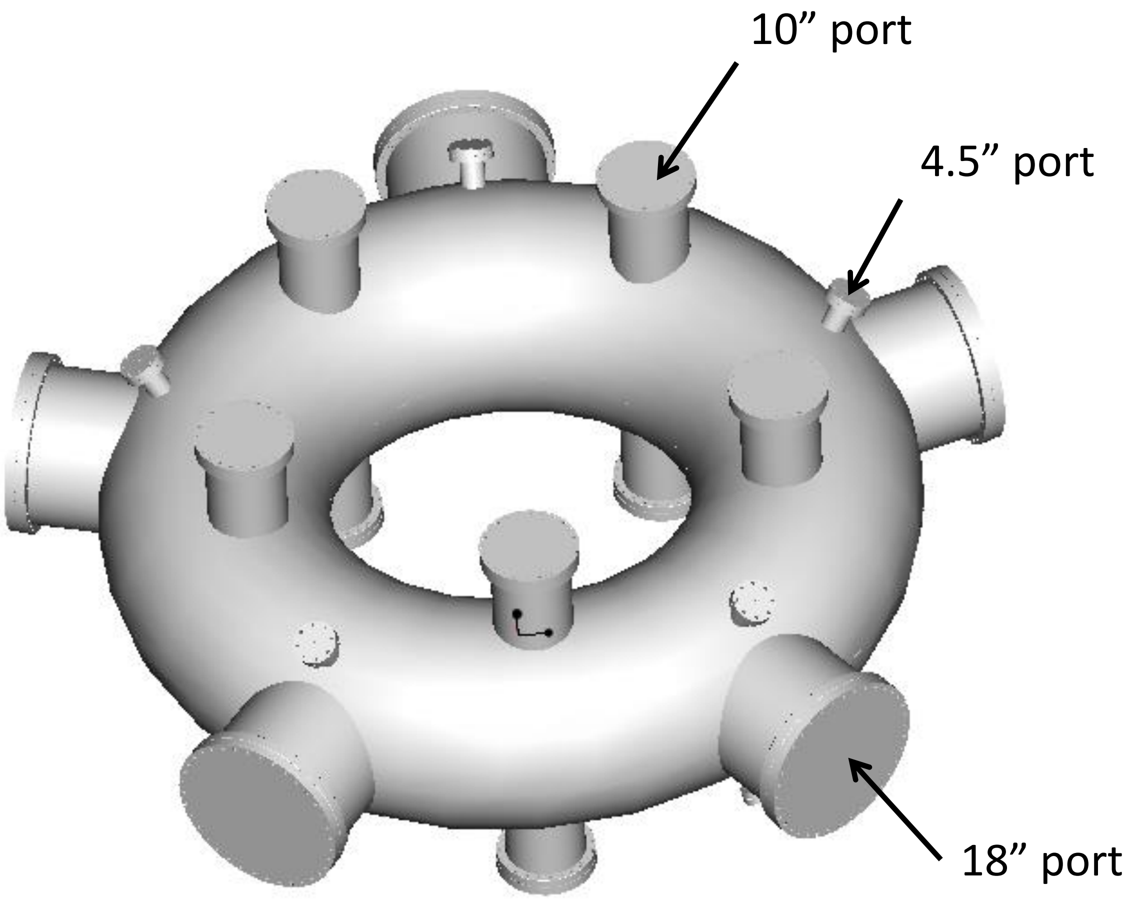
- R_0=75cm
- a_{vv}=29cm
- Volume - 1.5m^3

- No electrical break

- Inconel®625
  - Higher resistivity than SS316
  - Lower permeability than SS316

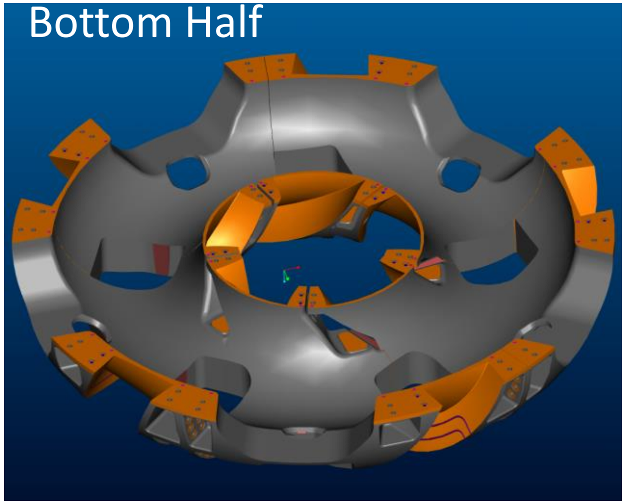
- Conflat style ports

- Pressure - 5 x 10^{-8} torr

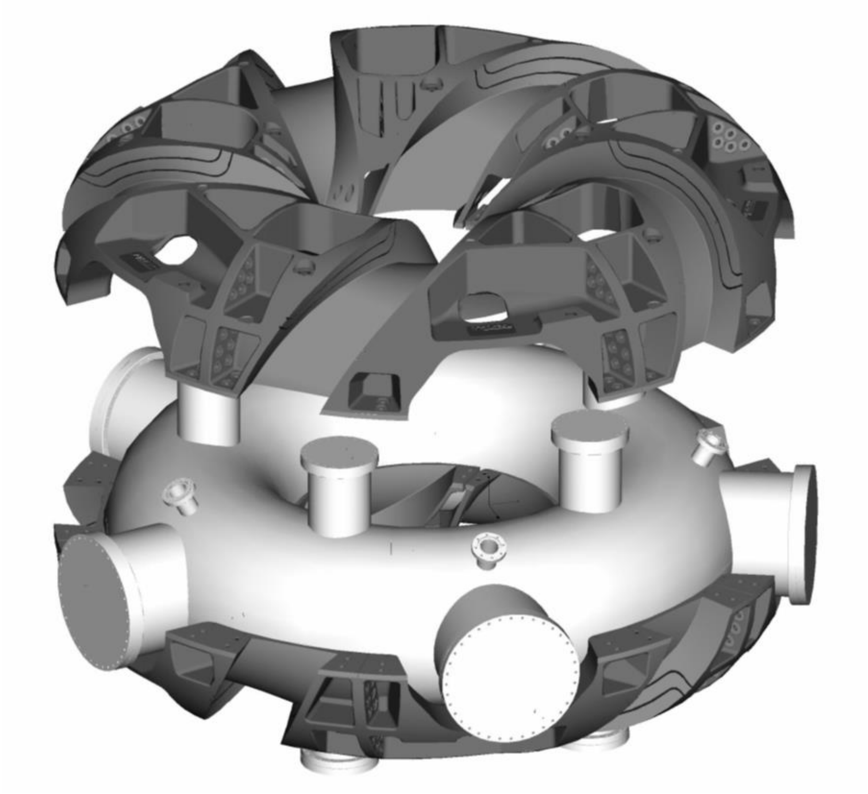


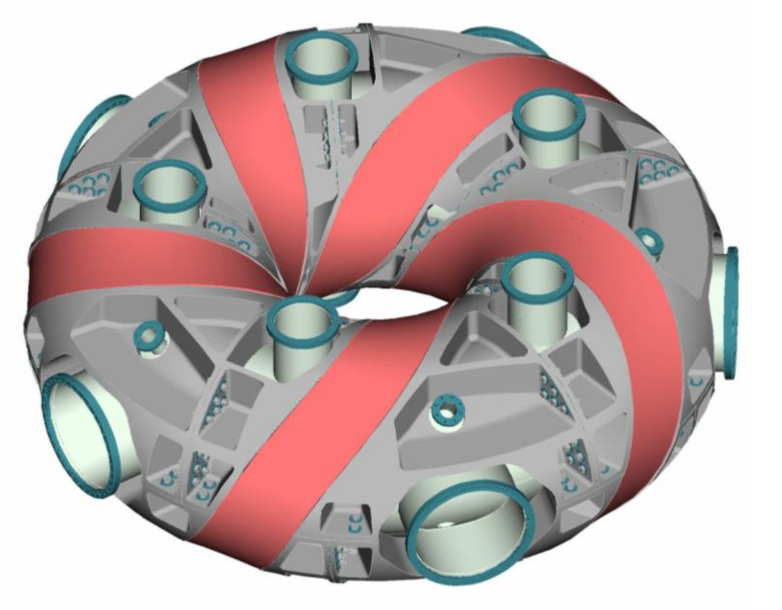
A Helical Coil Frame holds the helical coil to within 0.4mm of its design position

- 10 identical pieces
- Cast in Aluminum
- Trough and mating faces machined to 0.015”
- Total weight - 2000kg
- Designed by Tom Brown - Princeton Plasma Physics Laboratory

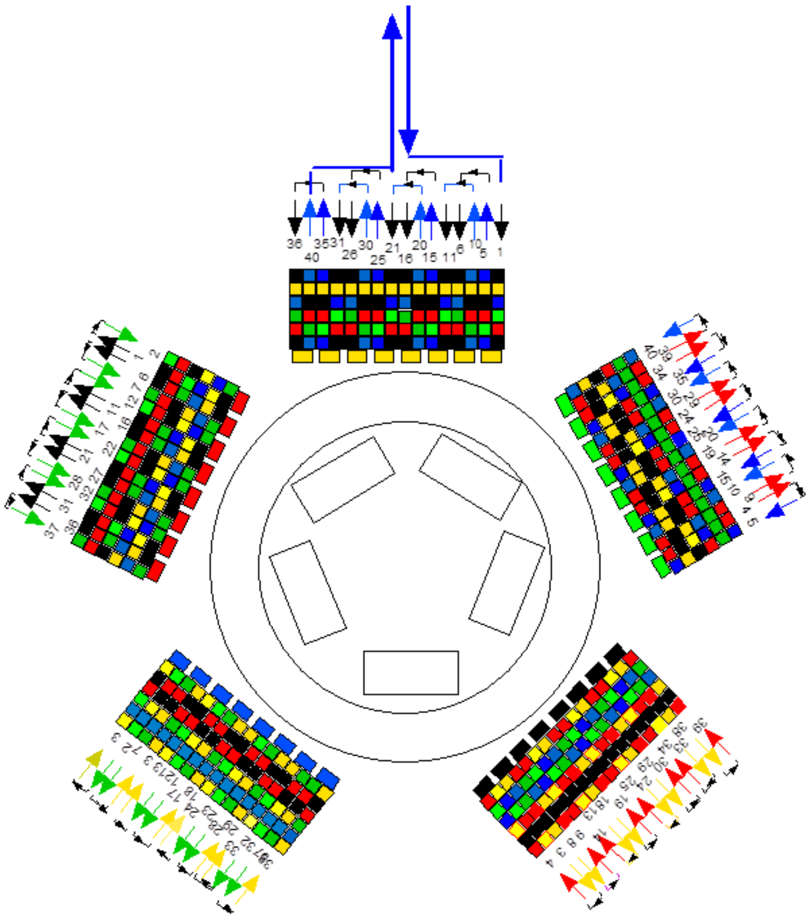


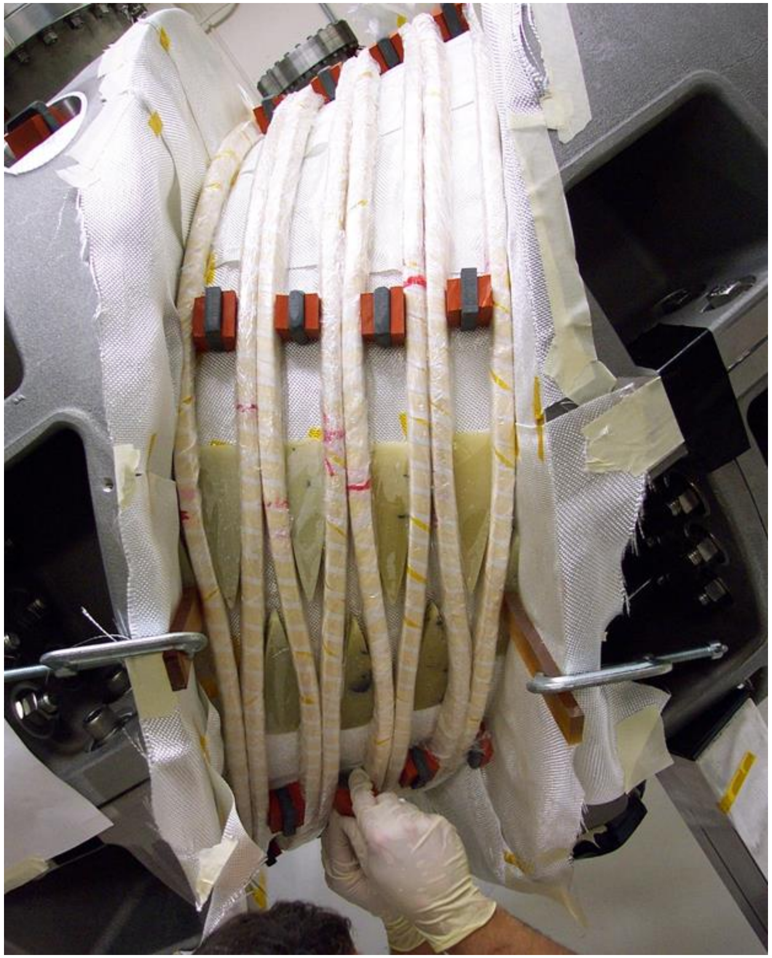
The vacuum vessel was encased in the frame and the helical coil wound



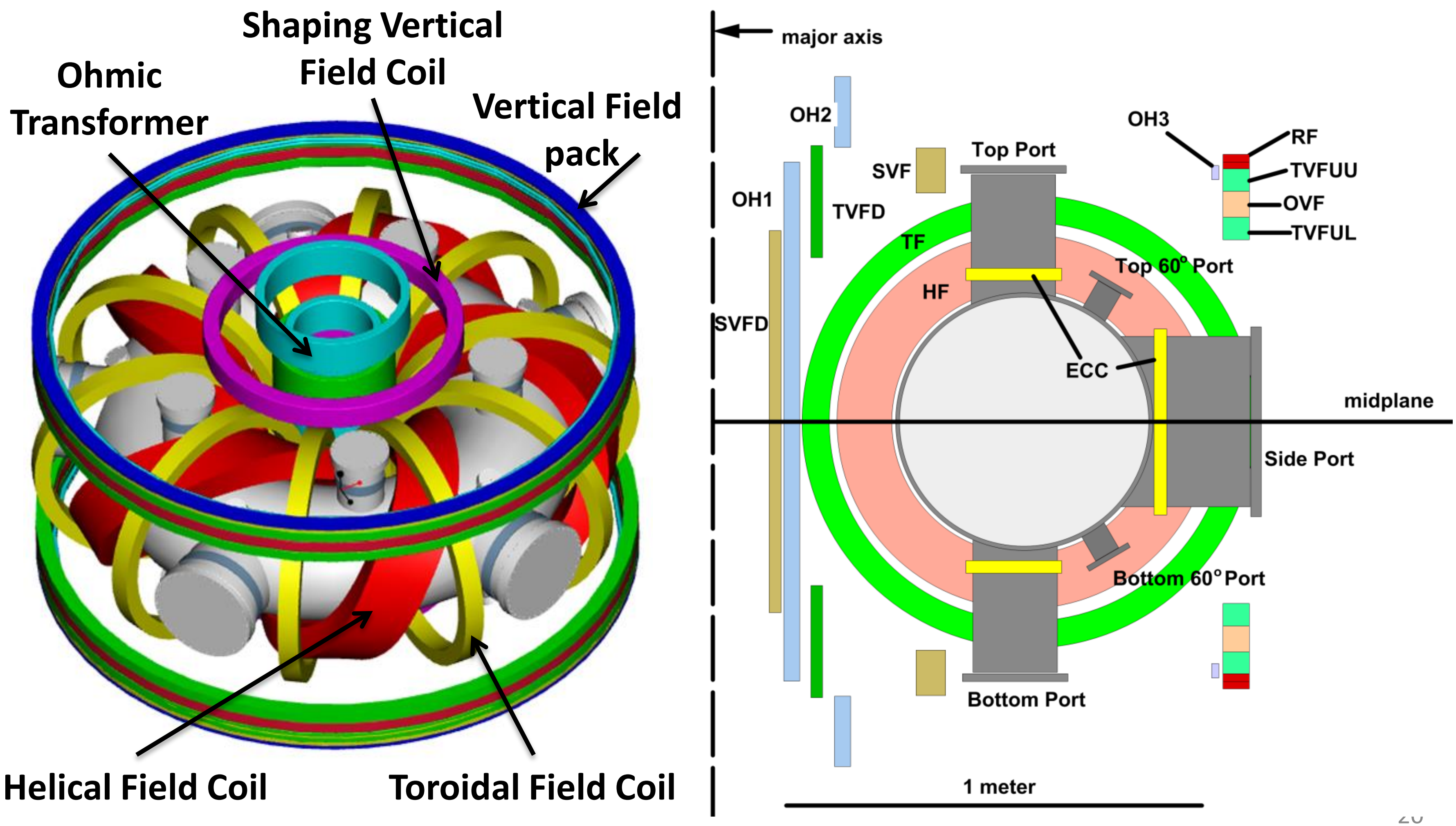


Magnet coils were wound to minimize magnetic dipoles and to maintain symmetry



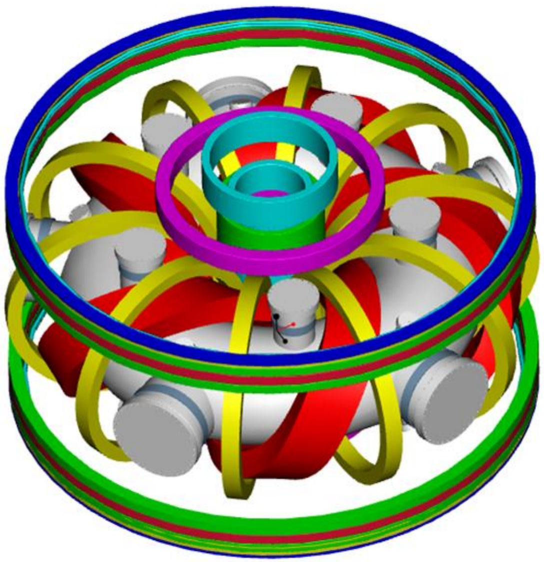


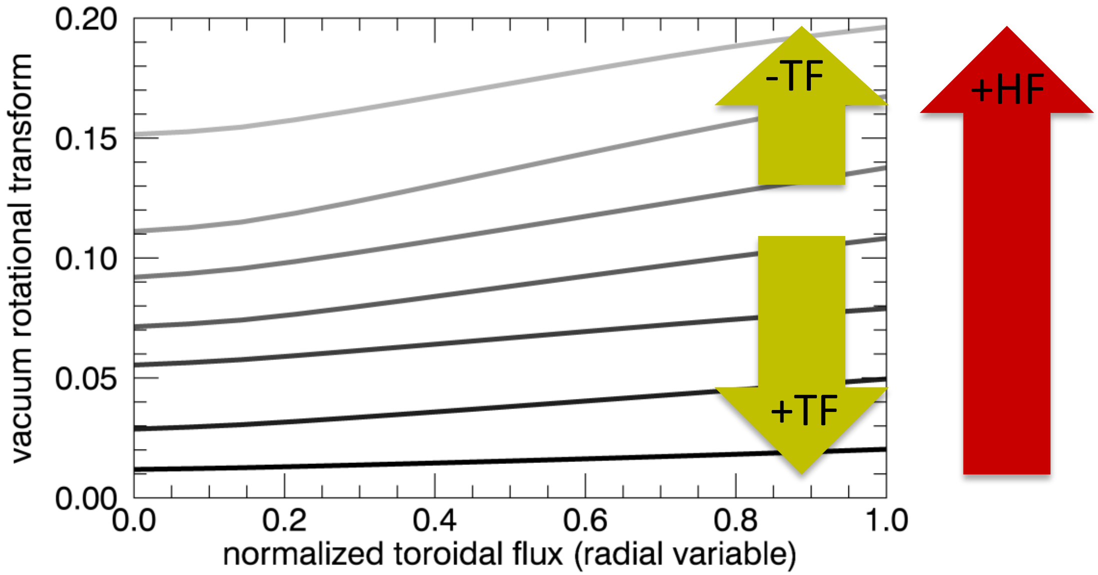
CTH has 7 independently controlled magnet coils



CTH has a very flexible magnetic configuration with vacuum transform variable by factor of 15

- **Helical Field coil** and **Toroidal Field coil** currents are adjusted to modify vacuum rotational transform: $0.02 < \iota_{vac}(a) < 0.33$

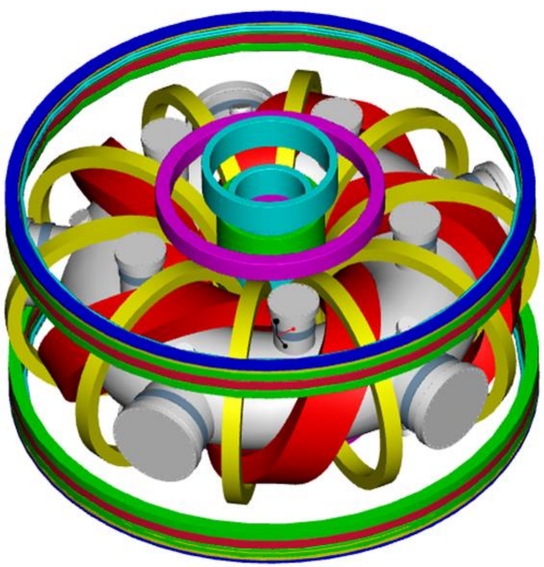


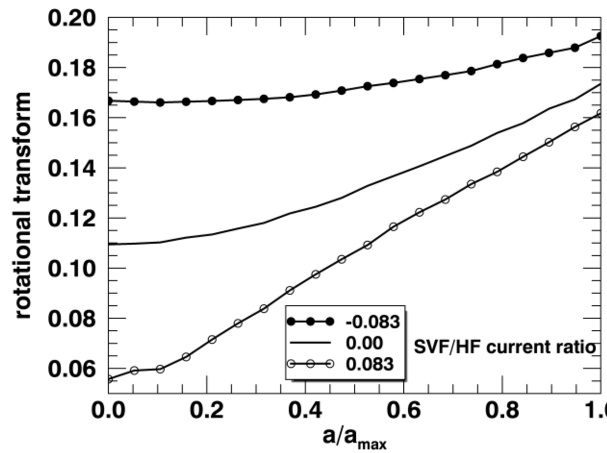


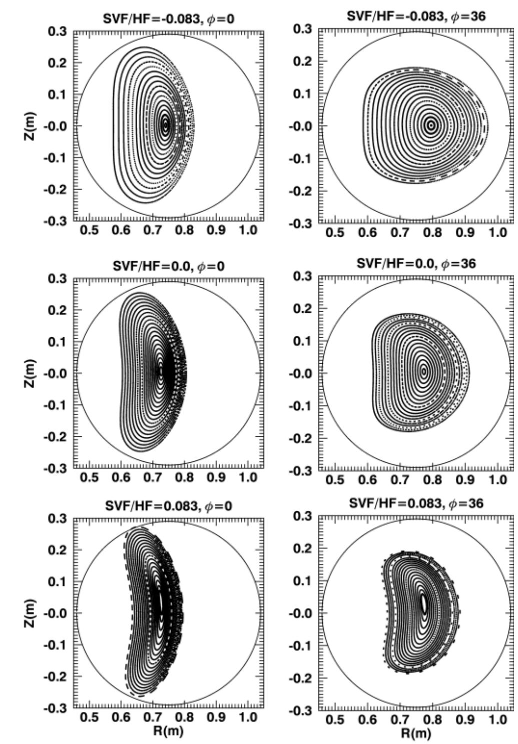
$$\iota \propto \frac{B_{poloidal}}{B_{toroidal}}$$

Plasma shape, horizontal and vertical position adjusted using addition coils

- **Helical Field coil** and **Toroidal Field coil** currents are adjusted to modify vacuum rotational transform: $0.02 < \iota_{vac}(a) < 0.33$



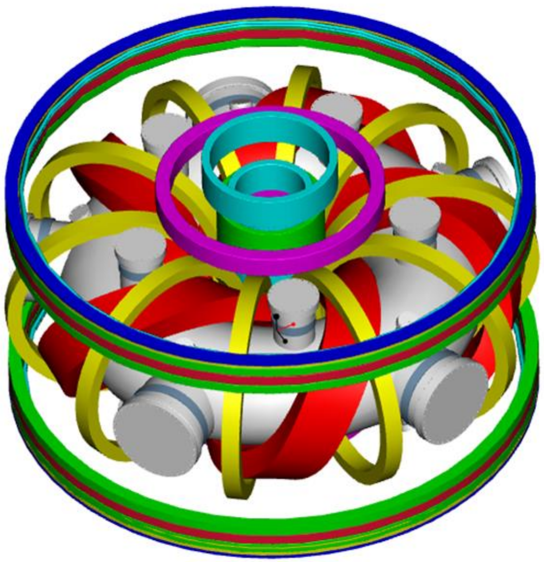


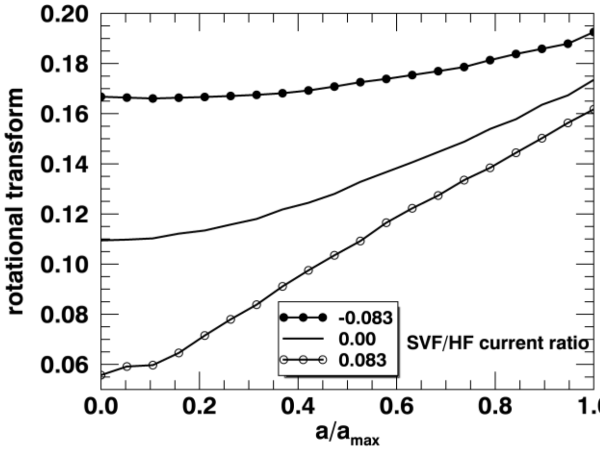


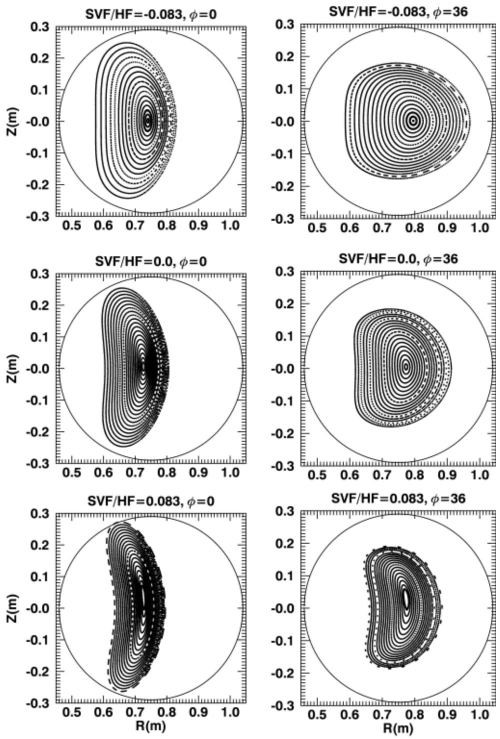
- **Shaping Vertical Field coil** varies elongation, κ, and shear, $d\iota/dr$

Plasma shape, horizontal and vertical position adjusted using addition coils

- **Helical Field coil** and **Toroidal Field coil** currents adjusted to modify vacuum rotational transform: $0.02 < \iota_{vac}(a) < 0.33$



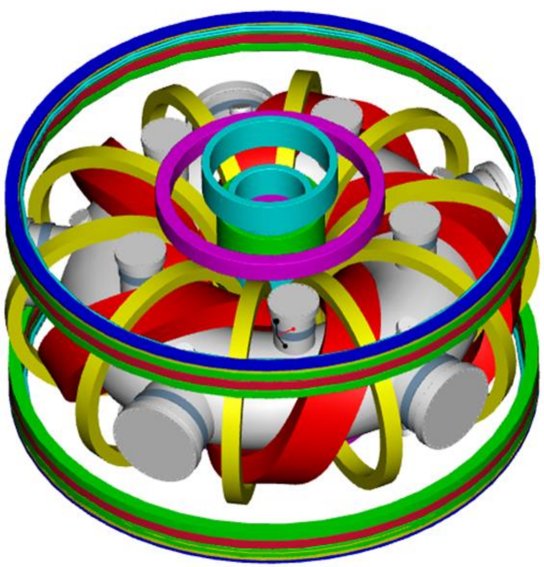


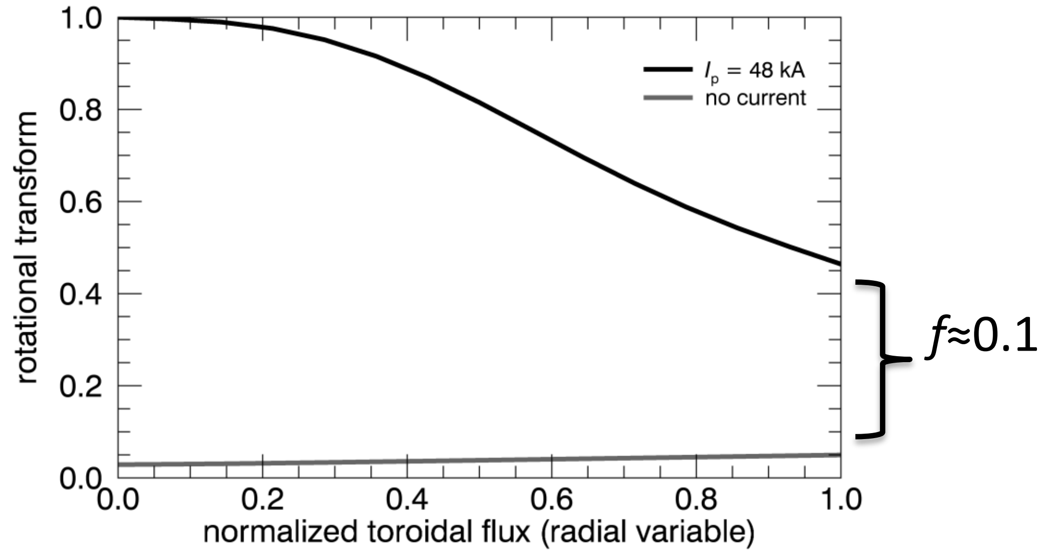


- **Shaping Vertical Field coil** varies elongation κ and shear
- **Trim Vertical Field coil** and **Radial Field coil** control horizontal and vertical positioning

Ohmic system drives plasma current

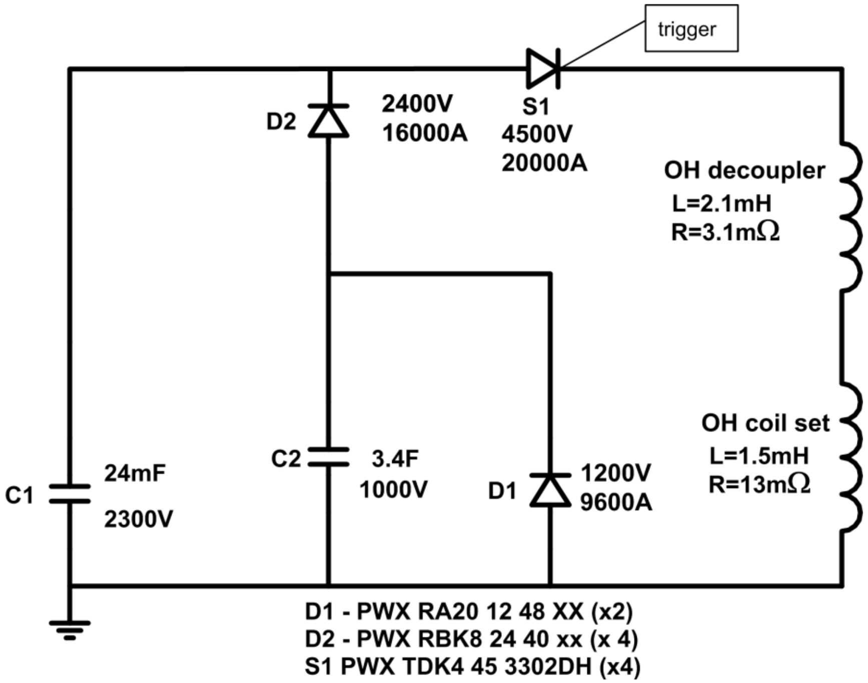
- **Central solenoid** drives up to 80 kA of plasma current
- Up to 95% of the total rotational transform is from plasma current

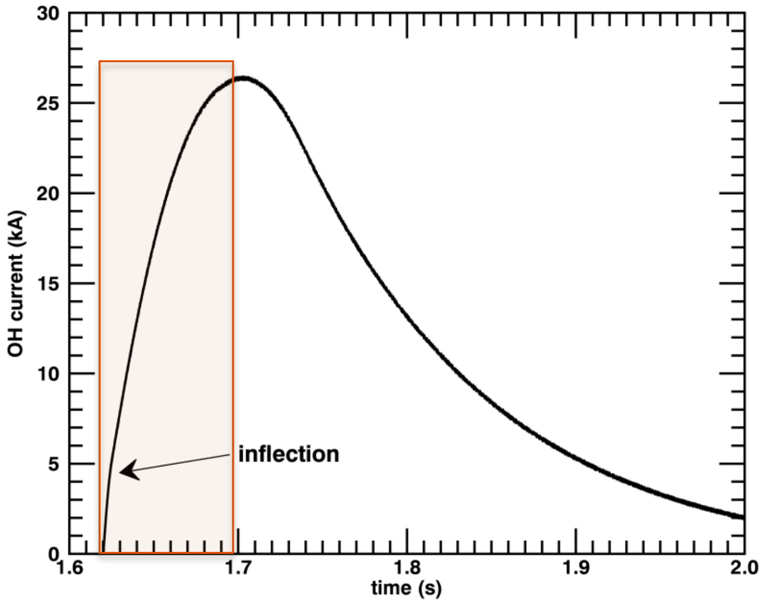




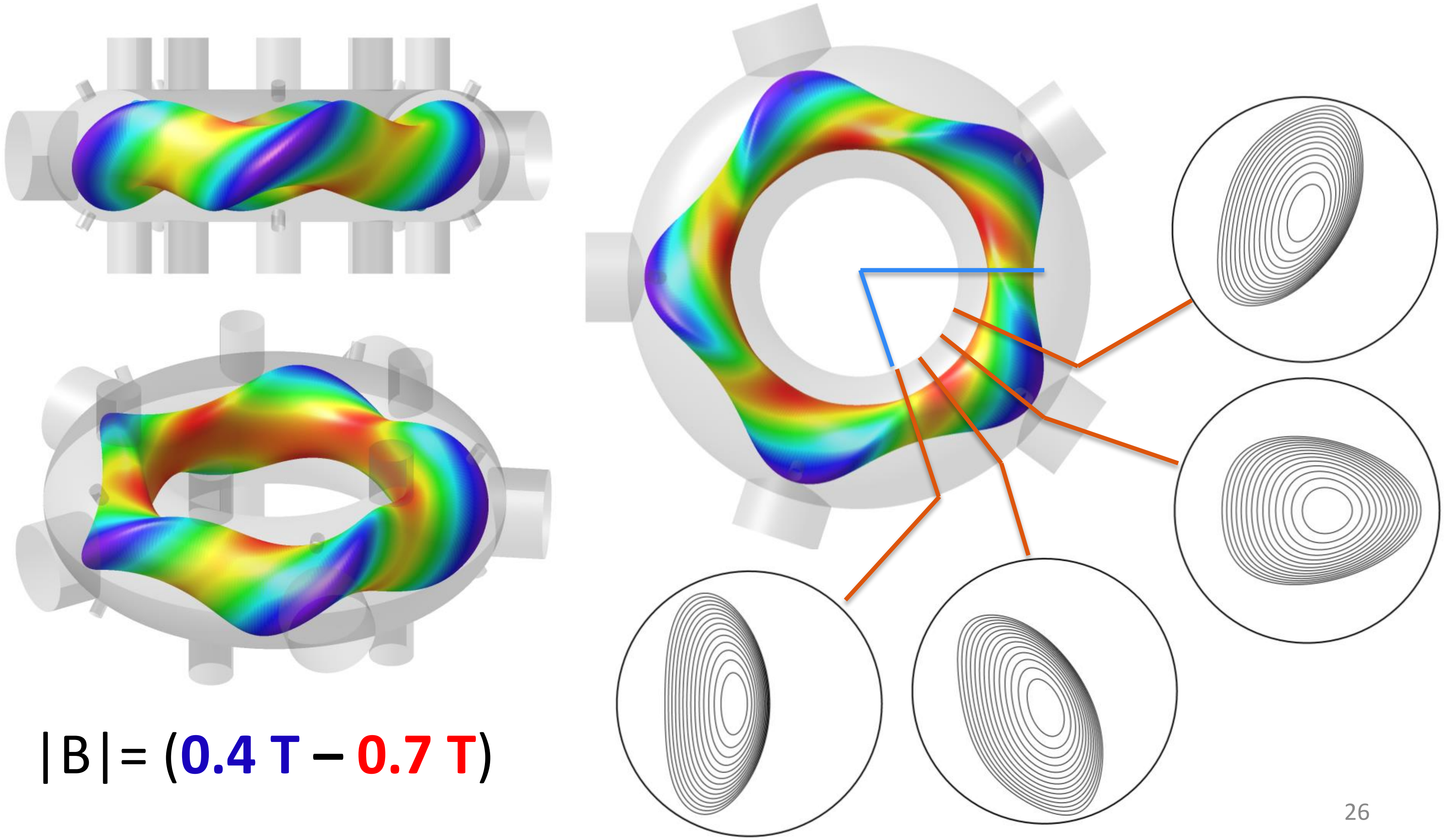
- Total rotational transform, $\iota_{total} = \iota_{current} + \iota_{vacuum}$
- Fractional transform, $f=\iota_{vac}(a)/\iota_{tot}(a)$

The OH circuit is a single swing design





CTH has a fully confining, three-dimensional flux surface shape



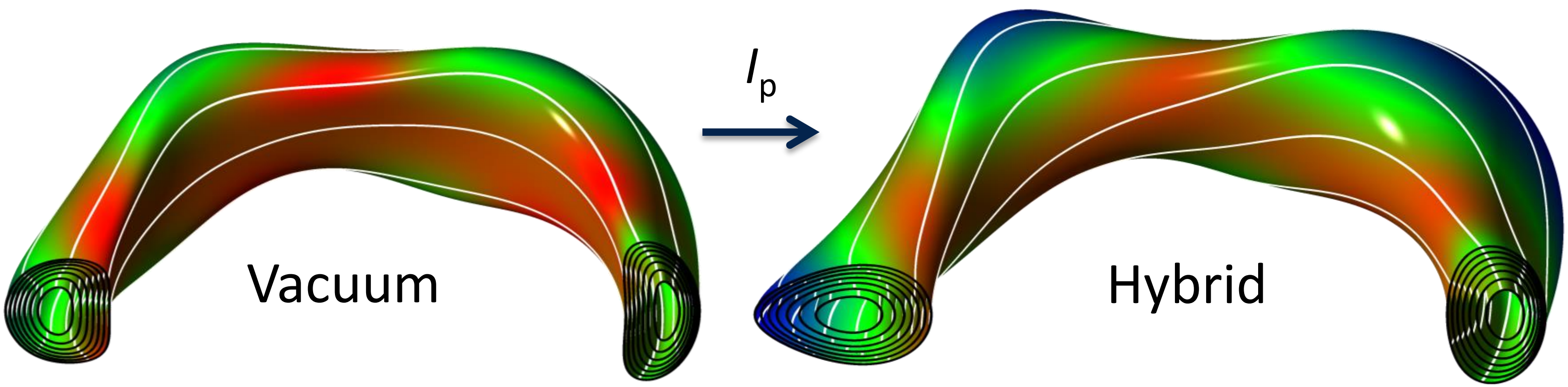
|B| = (0.4 T – 0.7 T)

CTH Diagnostics

- 3-chord 1mm microwave Interferometer
- Poloidal and toroidal B-dot probe arrays
- Rogowski coils
- 60 channel, dual energy, Soft X-Ray array
- SXR/bolometer arrays
- SXR spectrometer
- H-alpha detectors
- Thomson Scattering (being installed)
- Coherence Imaging (being installed)

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

- Plasma current strongly modifies the CTH equilibrium



- V3FIT[1] finds an MHD equilibrium most consistent with data, $\boldsymbol{d}$
- CTH uses VMEC[2] to model the equilibrium with parameters, $\boldsymbol{p}$

$$\chi^2 = \sum_i \left(\frac{S_i{}^o(\boldsymbol{d}) - S_i{}^m(\boldsymbol{p})}{\sigma_i{}^S} \right)^2$$

[1]J.D. Hanson et al., *Nucl. Fus.*, 2009, [2]S.P. Hirshman et al., *Comp. Phys. Comm*. 1986

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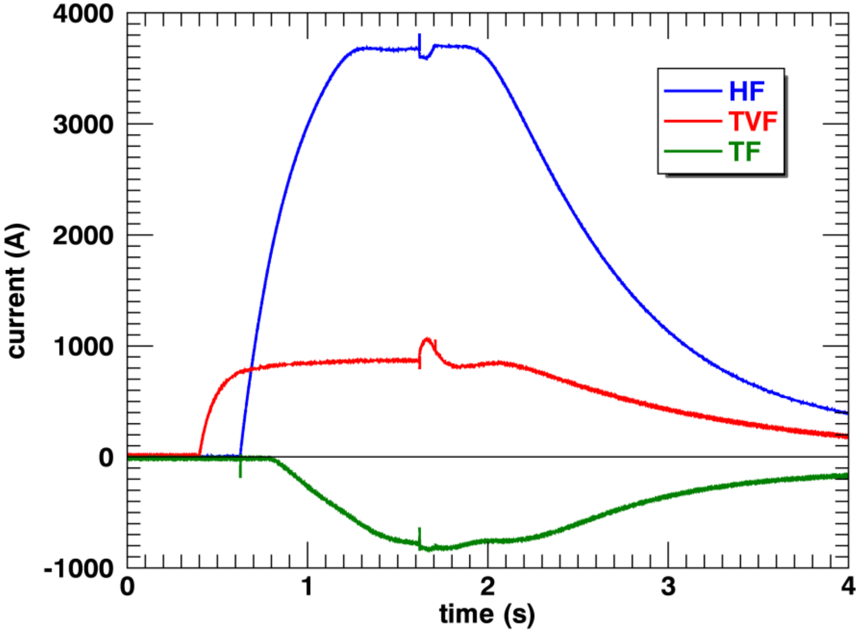
CTH Shot starts when the magnet currents turn on

10 Motor/Generators

Magnet Currents



CTH Shot starts when the magnet currents turn on

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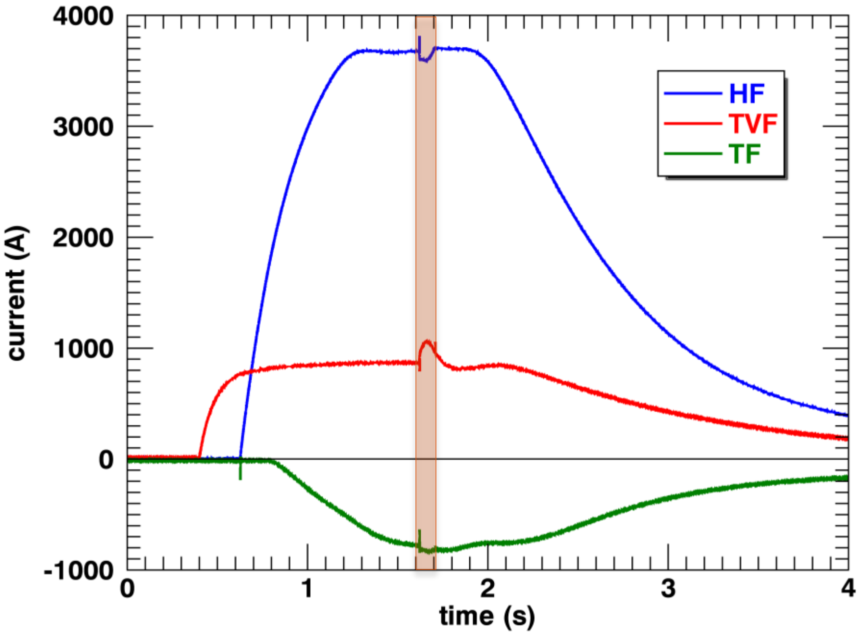
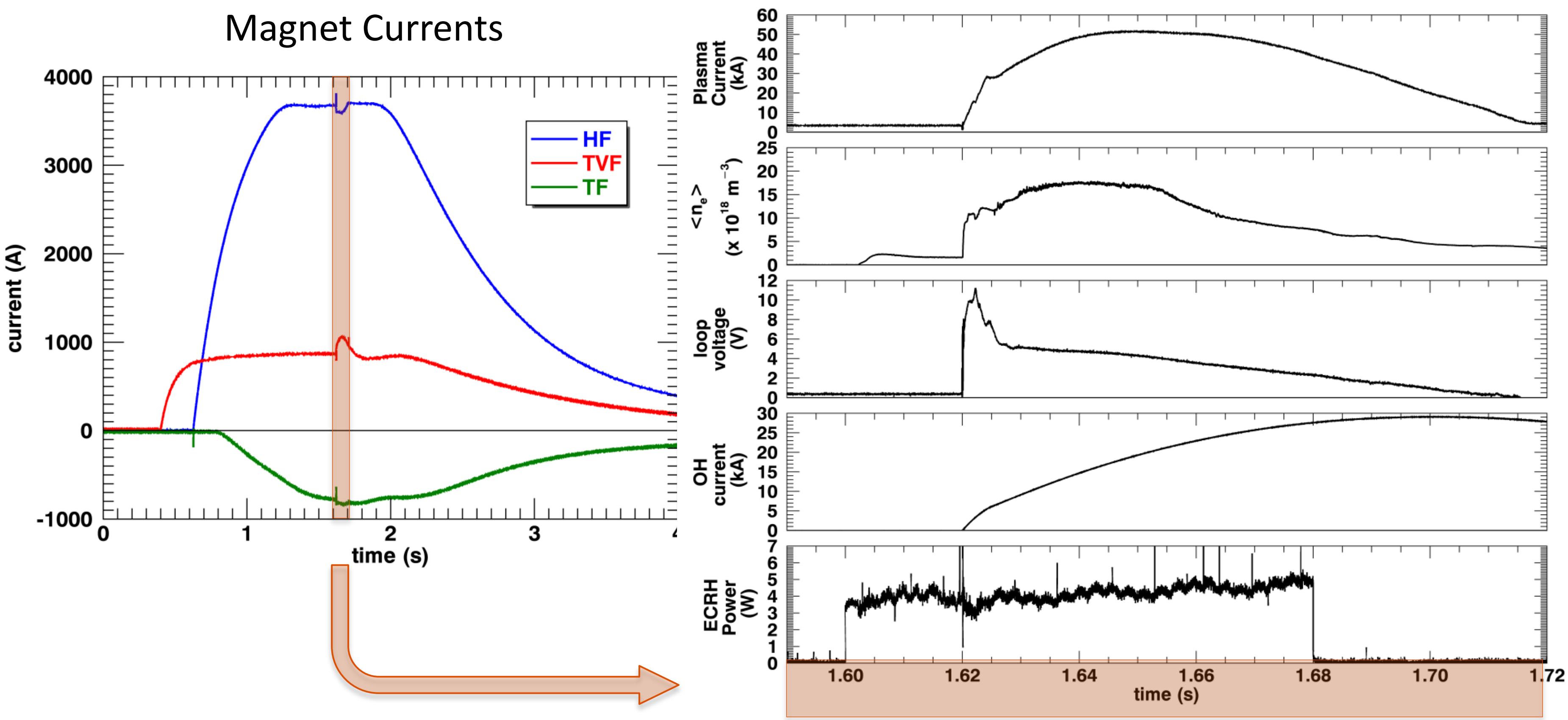
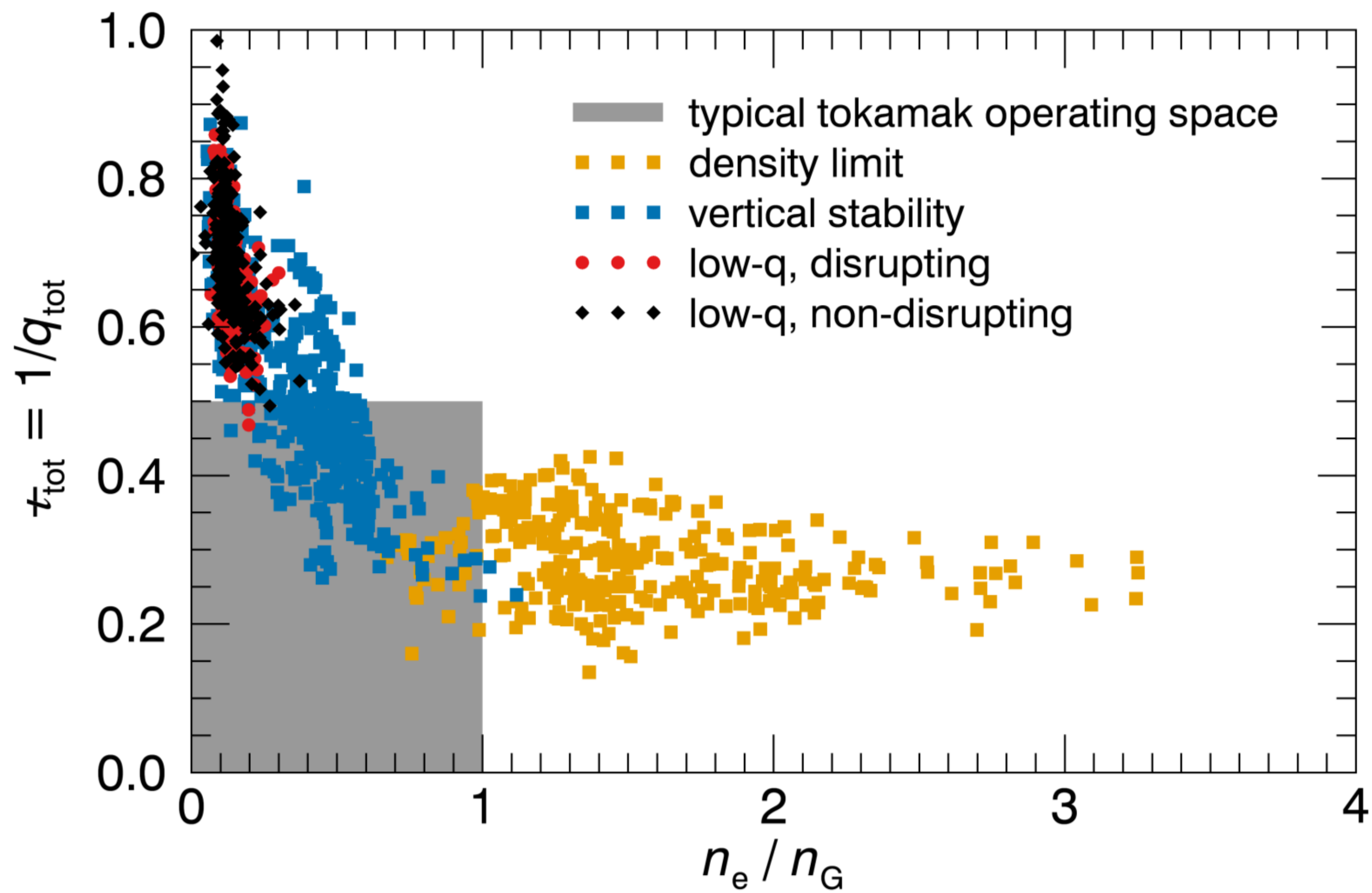


ECRH and ohmic power build up the plasma



Overview of CTH operational space and three types of disruptions observed



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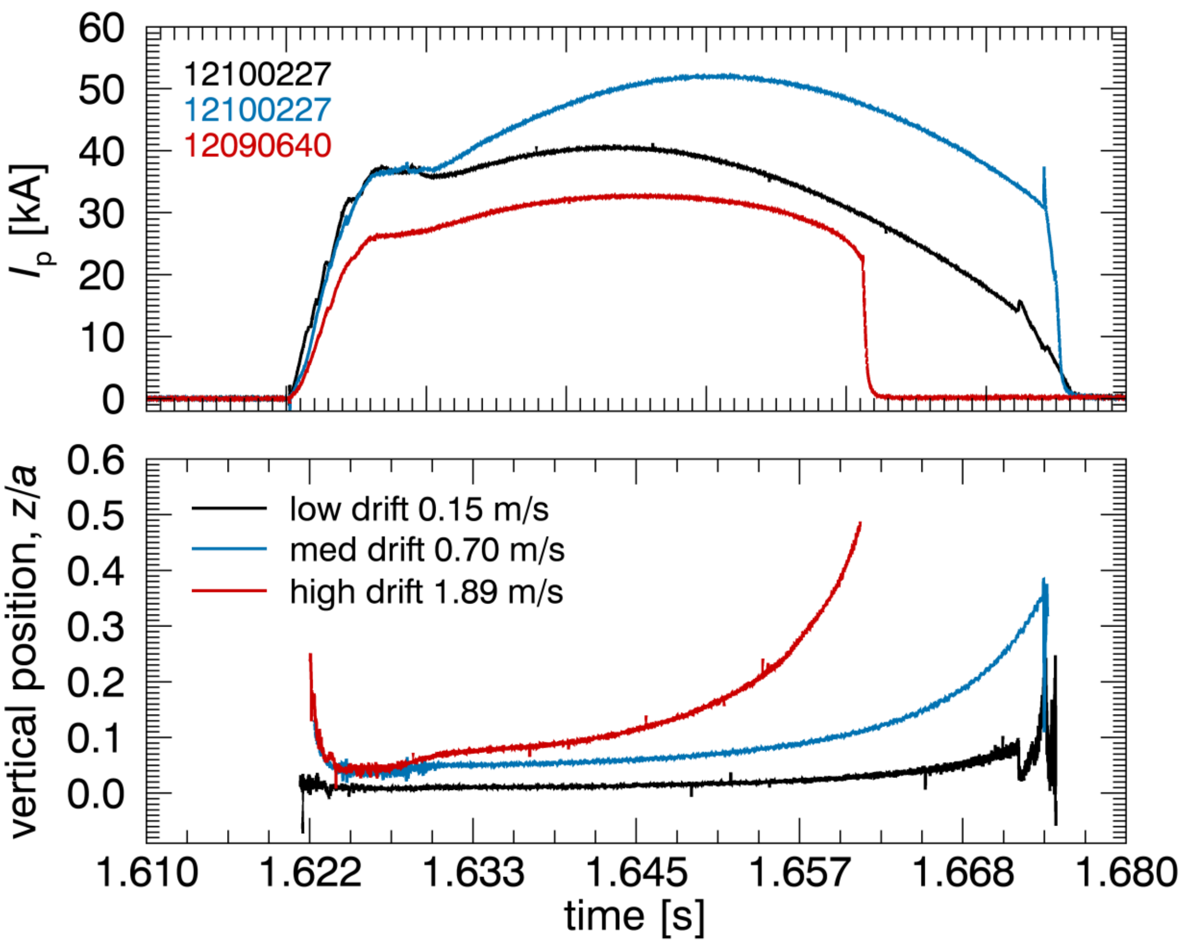
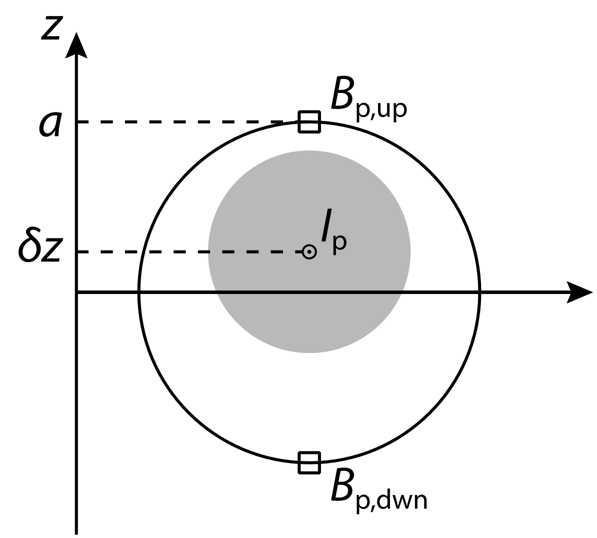
Elongated plasmas are vertically unstable

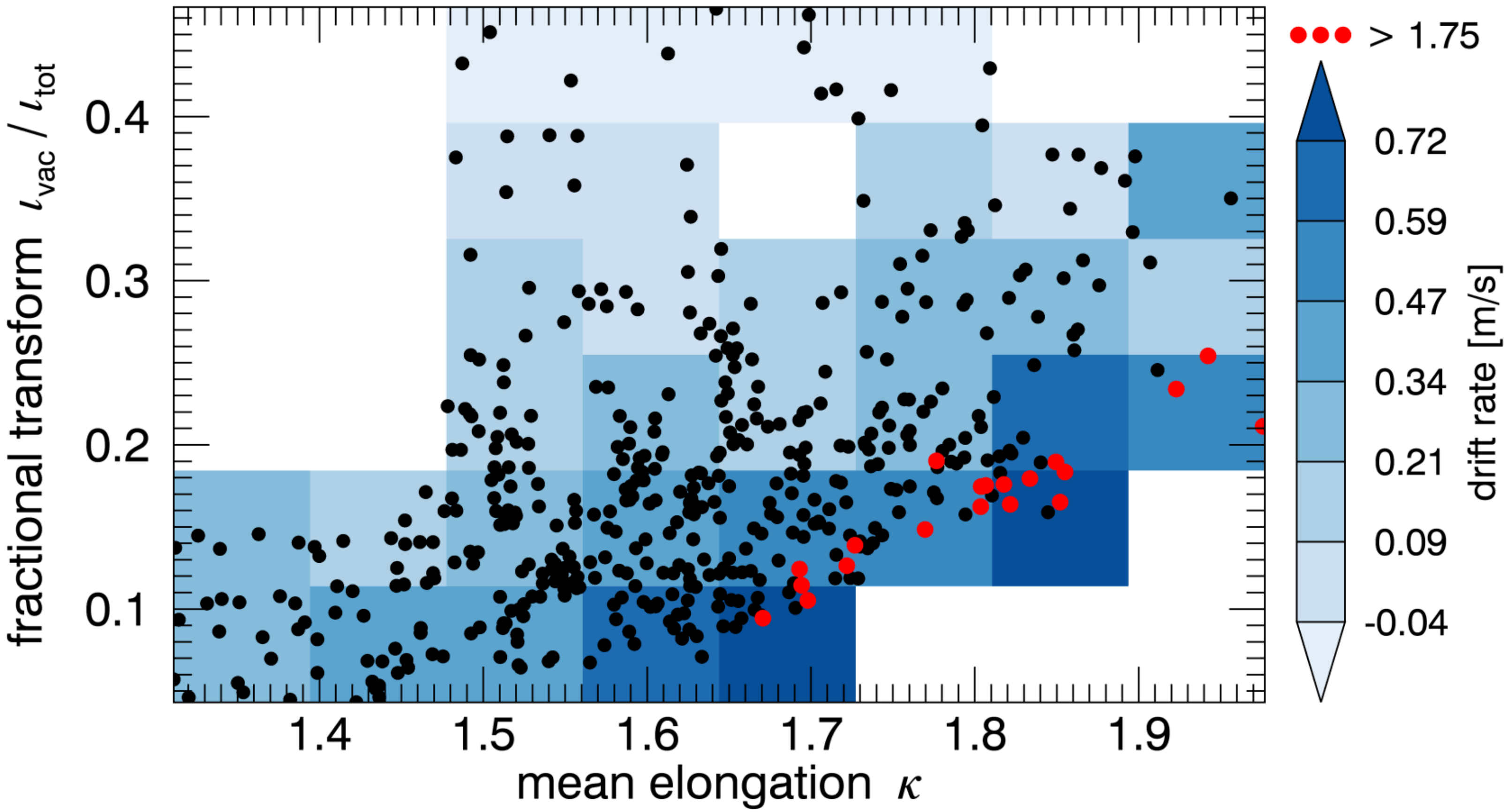




$$\frac{\delta z}{a} = \frac{B_{\mathrm{p,up}} - B_{\mathrm{p,dwn}}}{B_{\mathrm{p,up}} + B_{\mathrm{p,dwn}}}$$

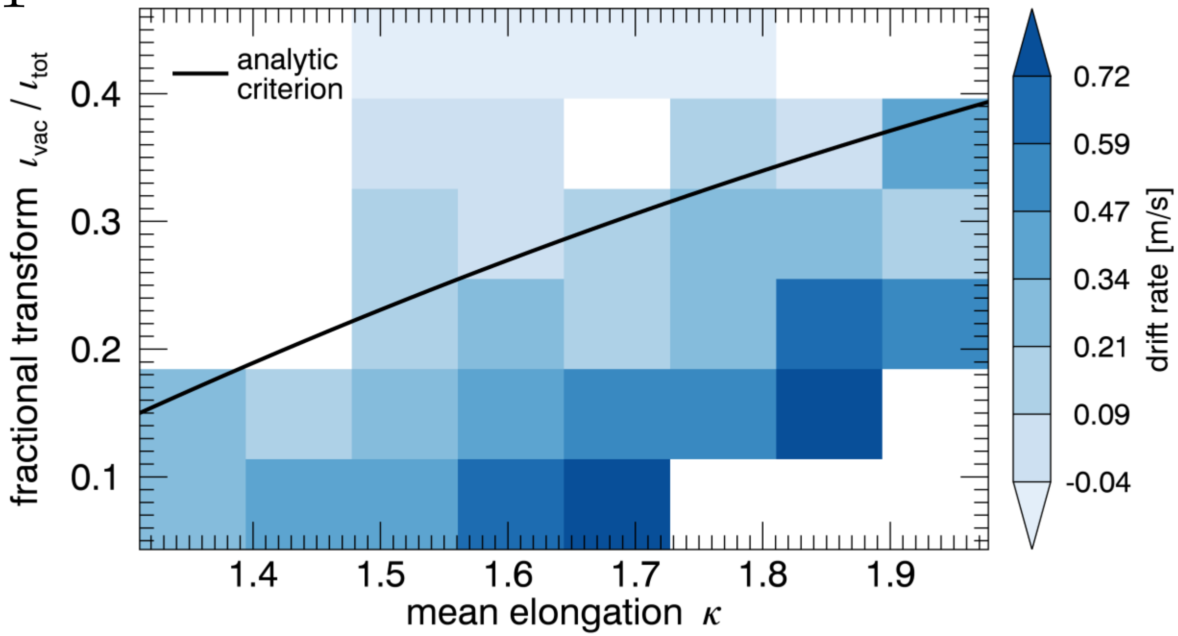
ArchMiller, et. al. *Phys. Plasmas* **21,** 056113 (2014).

Plasmas with high elongation stabilized by addition of vacuum transform



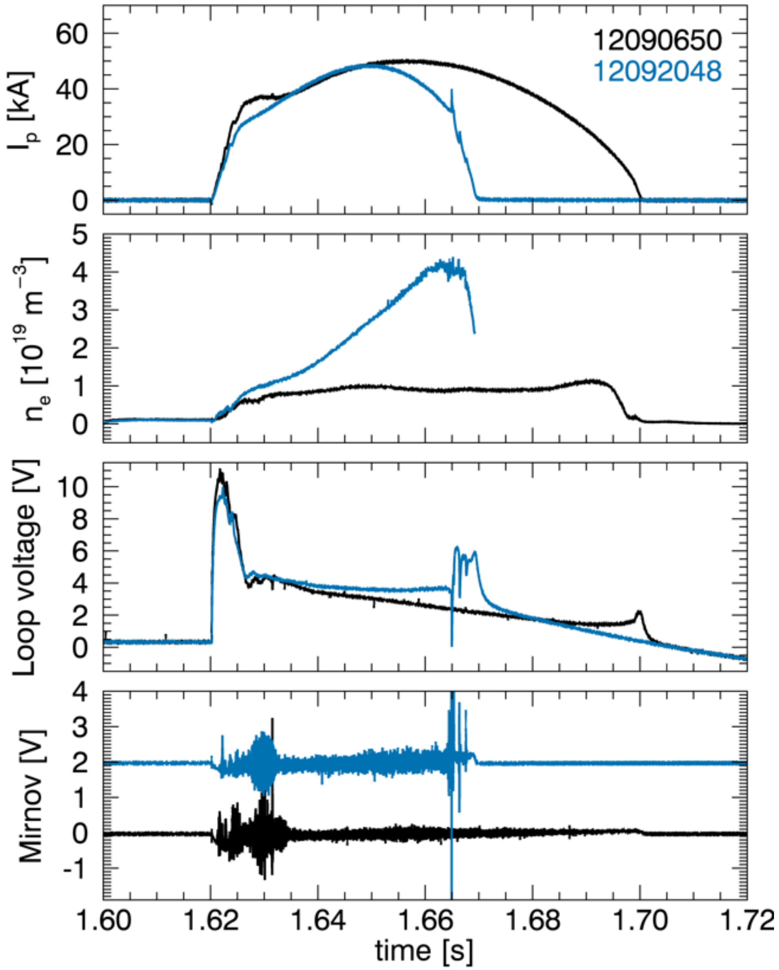
Qualitative agreement with analytic criterion for vertical stability

- 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

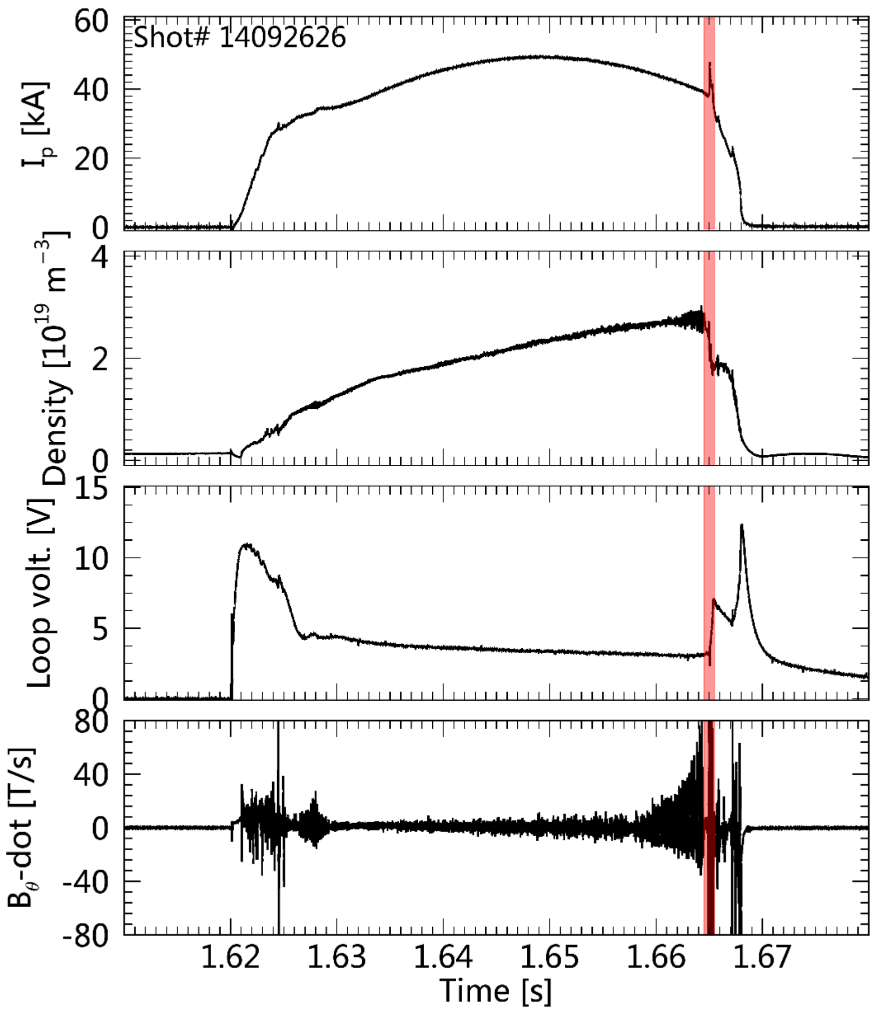


Density limit disruption can be triggered by elevated density with edge fueling

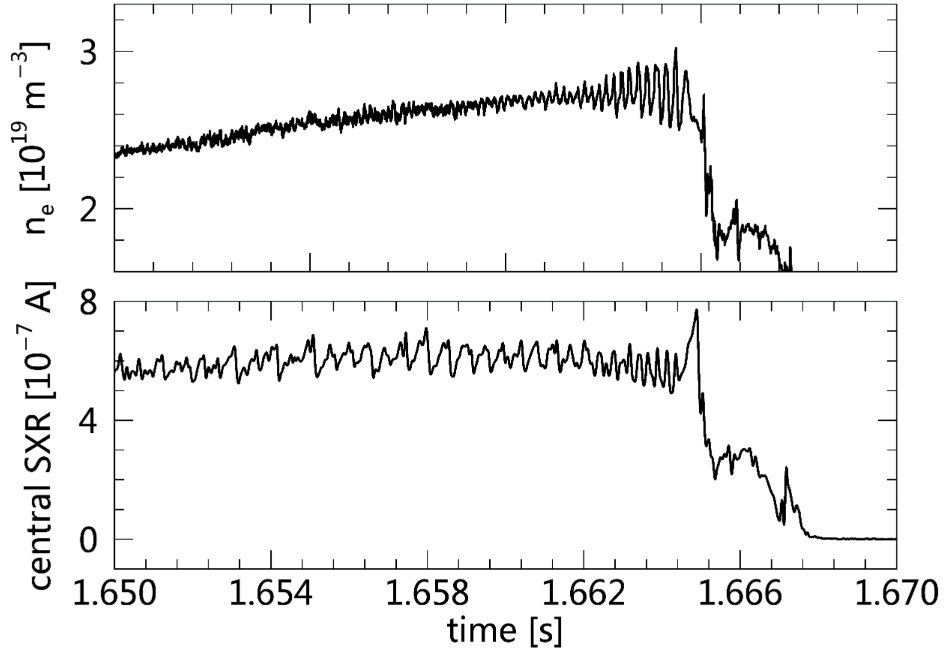
- Two discharges with similar vacuum transform ι_{vac} = 0.05.
- A high density shot achieved by ramping the density is observed to disrupt. A lower density discharge maintained at $n_e \approx 1 \times 10^{19} m^{-3}$ did not disrupt at this current.
- Phenomenology of hybrid discharge terminations similar to tokamak disruptions
    - Negative loop voltage spike
    - Current spike followed by rapid decay
    - Strong coherent MHD precursor



Disruption precursor fluctuations indicate internal tearing mode

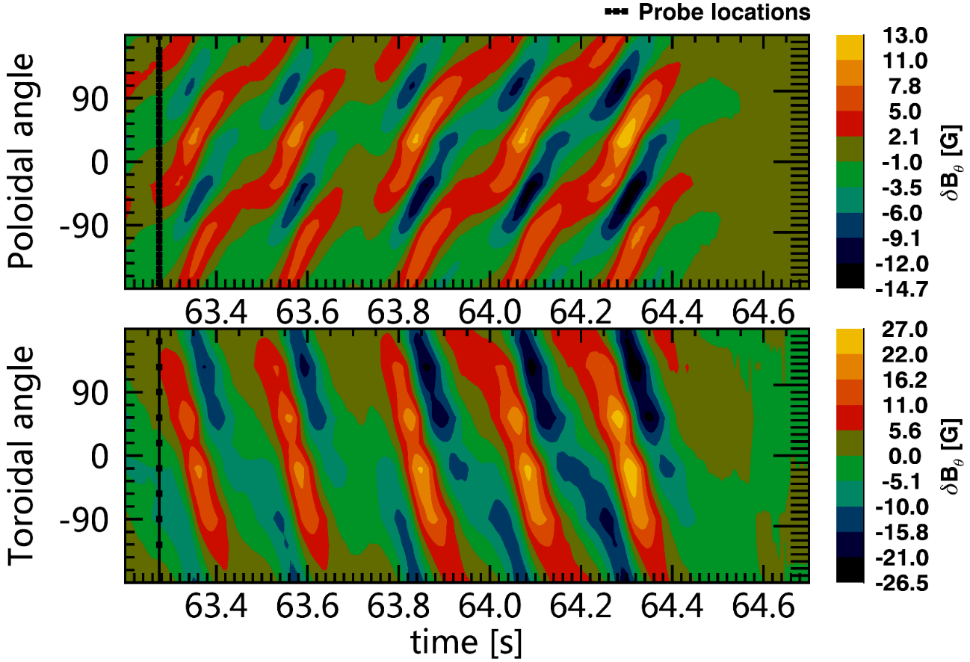


- MHD modulates density and SXR emission



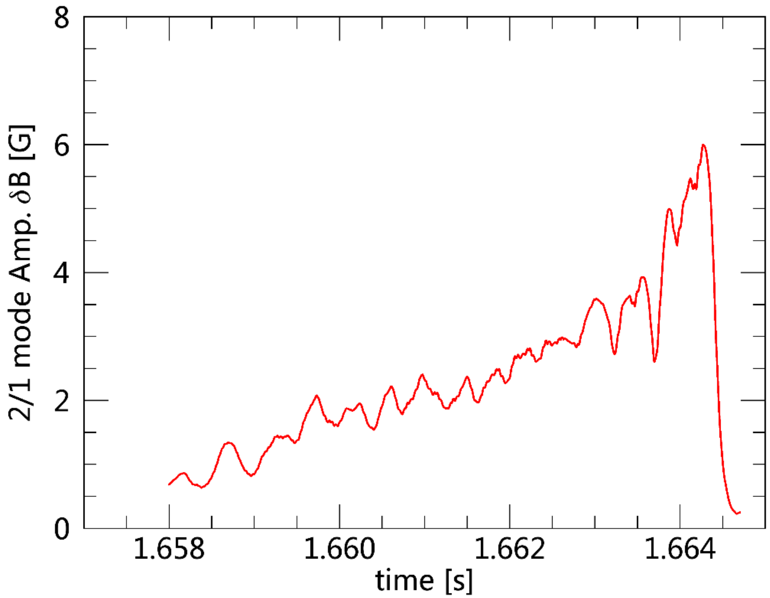
A growing m/n=2/1 tearing mode identified from B-dot probe measurements

B-dot probe signal amplitudes

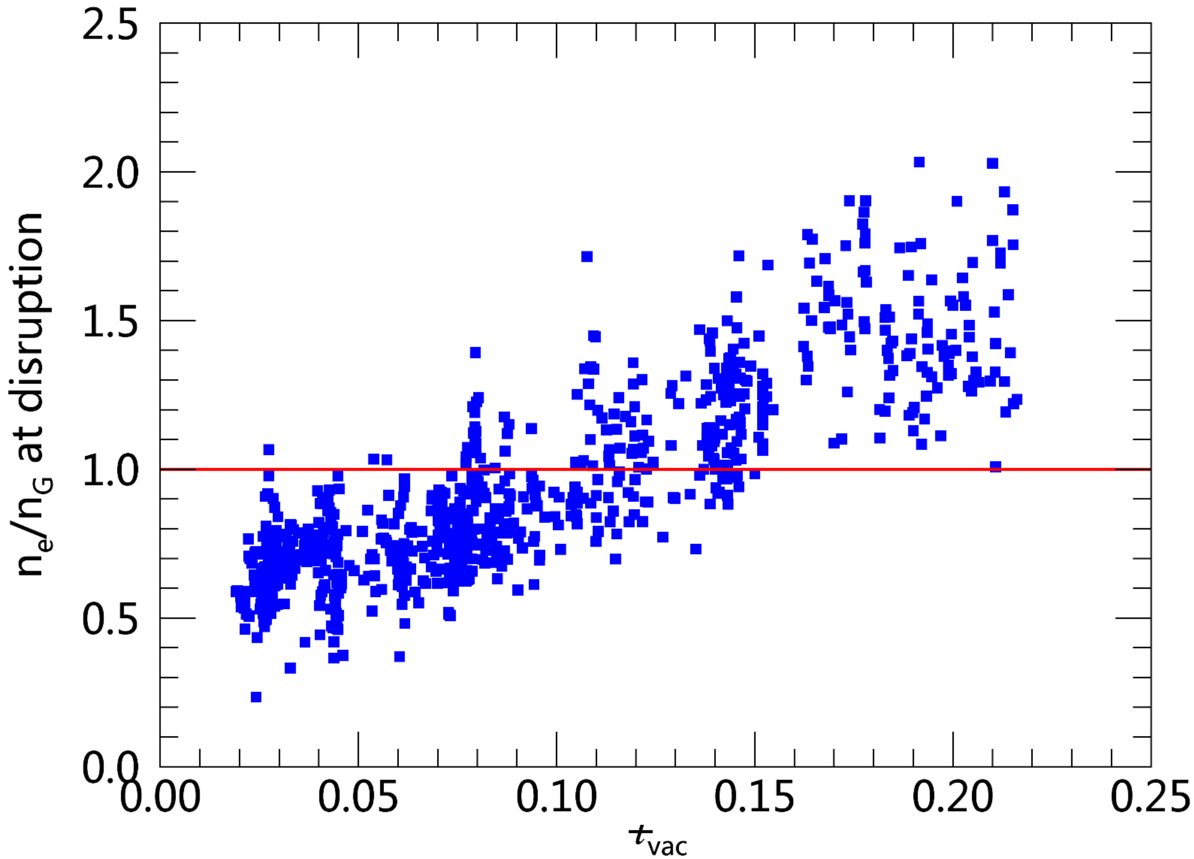


(time relative to 1.62s)

2/1 mode amplitude

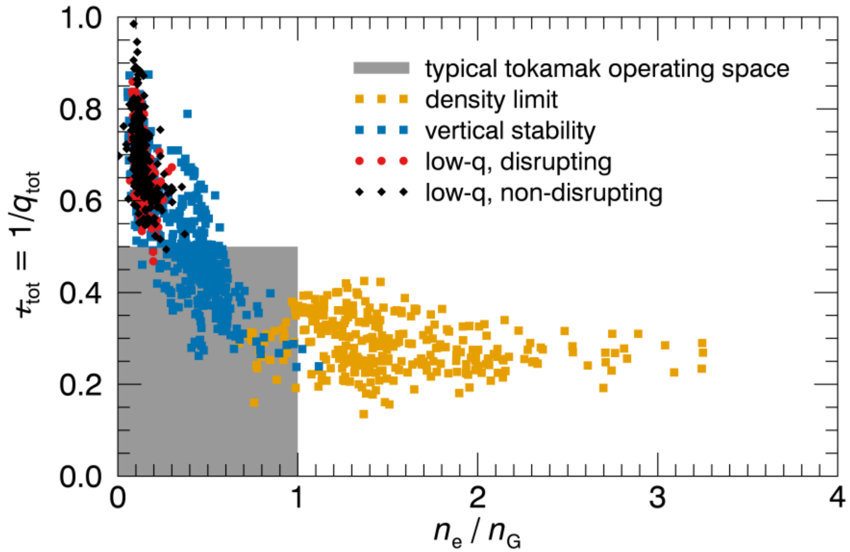


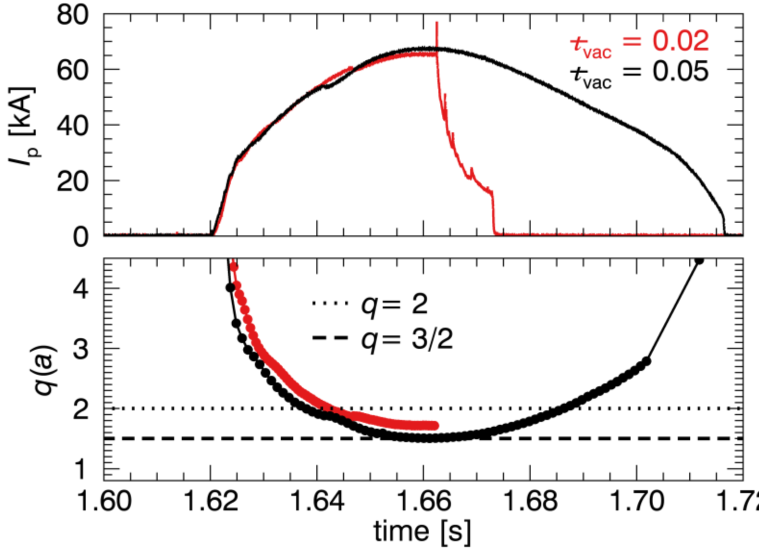
Density at disruption exceeds Greenwald limit as vacuum transform is increased



- Normalized density limit increases by a factor of nearly 4 as the vacuum transform is raised.

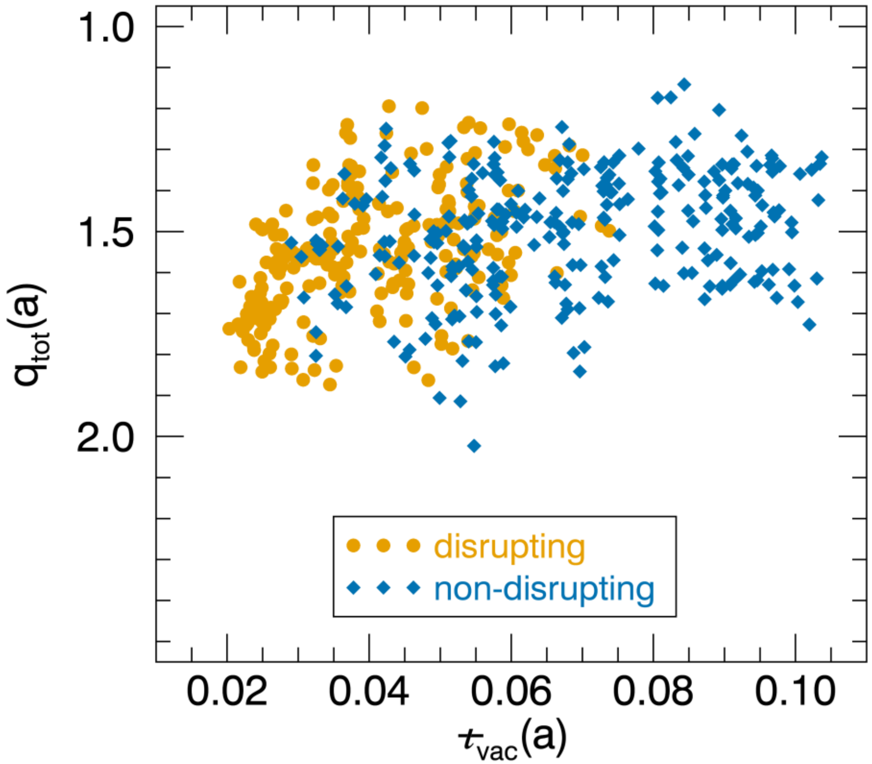
CTH can operate beyond the $q(a)$ = 2 current limit, with a slight increase in ι_{vac}





- Density limit disruptions
- Vertically unstable plasmas
- Low-q disruptions

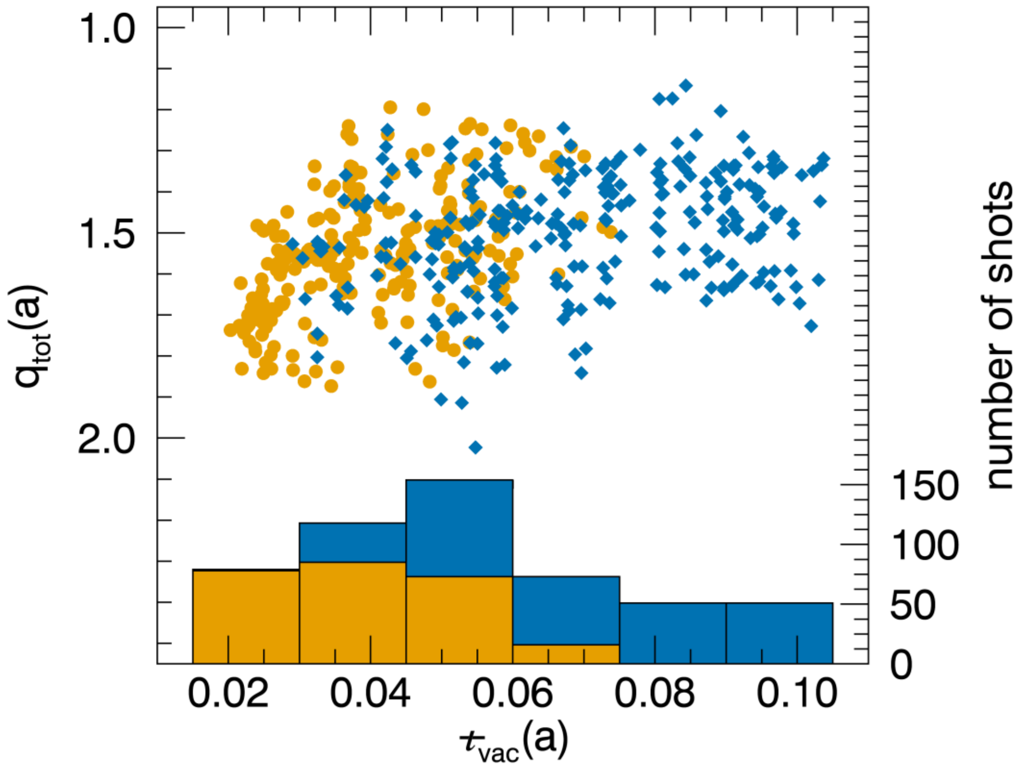
Disruption suppression starts when ι_{vac}>0.03 while disruption free operation for ι_{vac}>0.07



- Ensemble of 526 discharges
- ι_{vac} varied while I_p ramp rates are kept similar
- $q_{tot}(a)$ computed at peak I_p
- Fast current quench for
  $\iota_{vac}(a)$< 0.03
- Fast/partial current quench and beginning of disruption suppression for 0.03<ι_{vac}<0.07
- Disruption free operation for ι_{vac}>0.07

Pandya, et. al. *Phys. Plasmas* **22**, 110702 (2015)

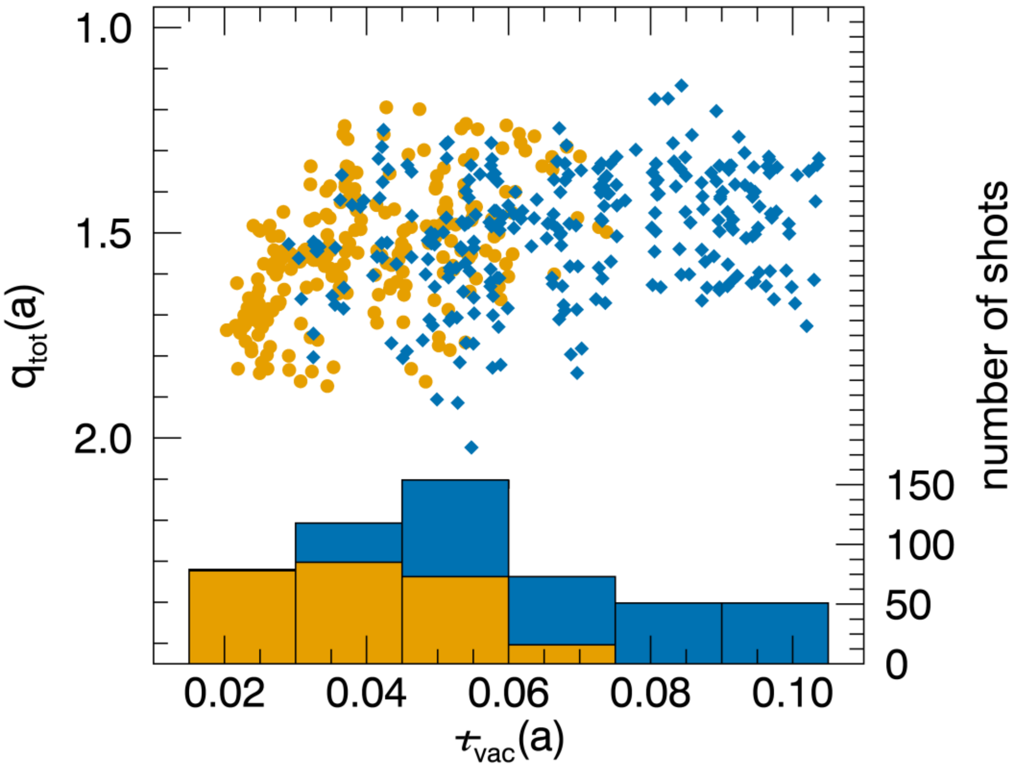
Disruption suppression starts when ι_{vac}>0.03 while disruption free operation for ι_{vac}>0.07

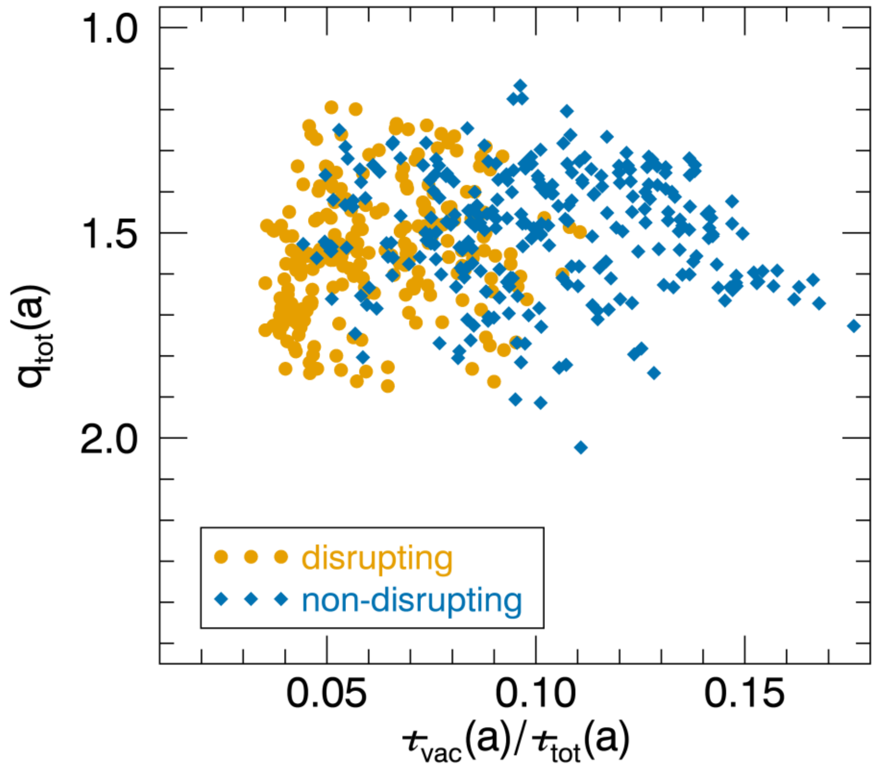


- Ensemble of 526 discharges
- ι_{vac} varied while I_p ramp rates are kept similar
- $q_{tot}(a)$ computed at peak I_p
- Fast current quench for $\iota_{vac}(a) < 0.03$
- Fast/partial current quench and beginning of disruption suppression for $0.03 < \iota_{vac} < 0.07$
- Disruption free operation for $\iota_{vac} > 0.07$

Pandya et al Phys. Plasmas 22, 110702 (2015)

Disruption avoidance achieved with fractional rotational transform, f ~ 10 %

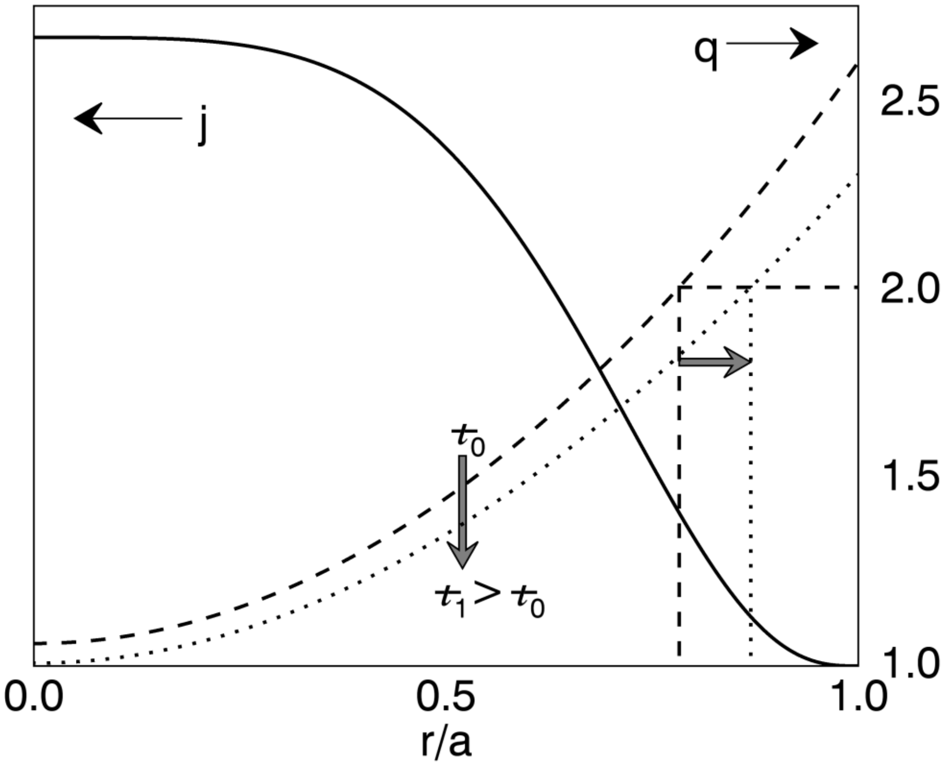




fractional transform

Conjecture for disruption suppression

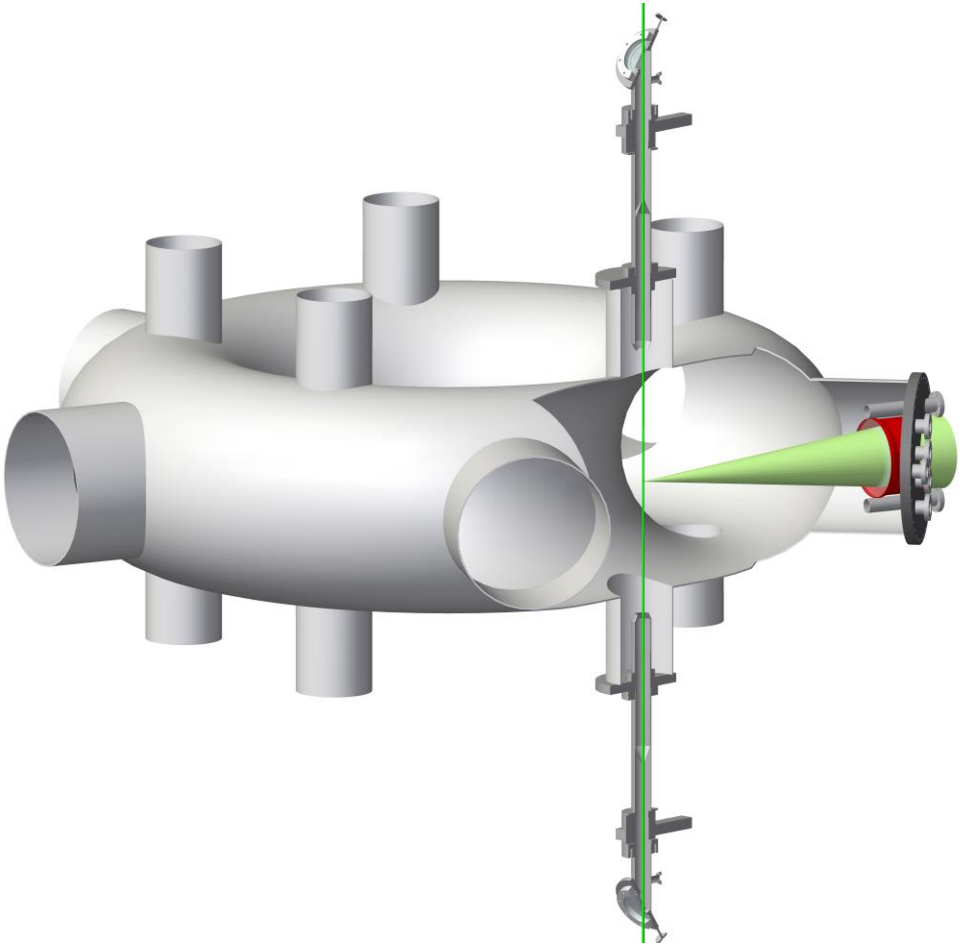
- Experiments on previous current-carrying discharges of W VII-A stellarator, have shown suppression of low-q disruptions with *f*>0.3.
- 2/1 kink mode was suppressed in this case.
- The disruption mitigation was conjectured to be shifting of rational surface to a region of smaller current density gradient with increasing external rotational transform.
- A similar mechanism may be responsible for disruption suppression on CTH.



Outline

- Fusion Energy and Magnetic Confinement
- Motivation
  - Disruptions
  - Mitigation
- CTH
  - Hardware
  - Operation
- Disruption Studies
  - Vertical Displacement
  - Density Driven
  - Low q
- Future work

Thomson scattering is under development

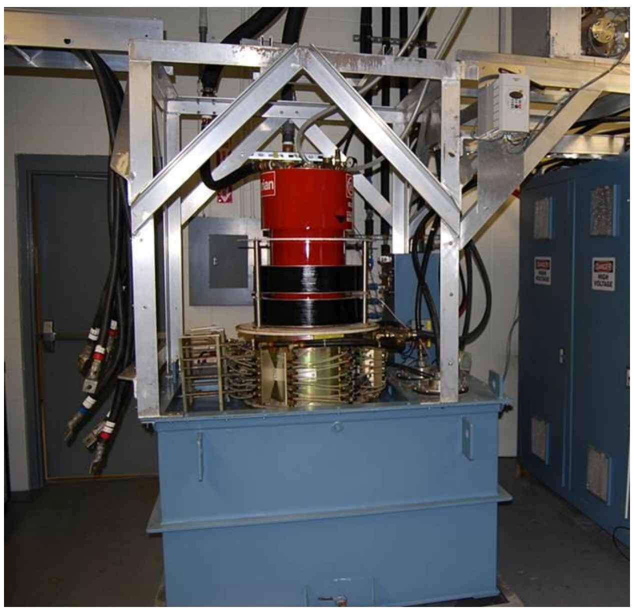


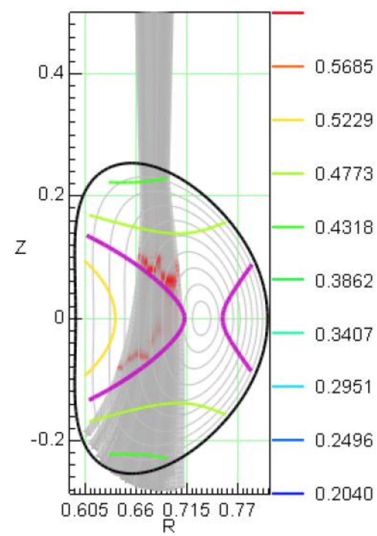
- Single point measurement initially with plans to upgrade to multi-point system
- Frequency doubled Nd:YAG (532 nm)
- High quantum efficiency PMT detector
- Will be used to calibrate SXR T_e measurements
- $T_{e\,,}$ n_e measurements will improve V3FIT reconstructions

P. J. Traverso, et al., *Rev. Sci. Instrum.* **85** 11D852 (2014)

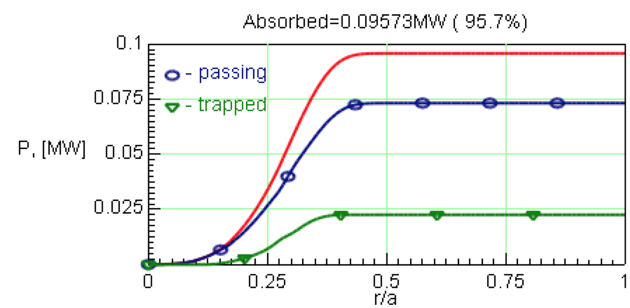
A 200KW, 28GHz gyrotron is being installed to give hotter plasmas for divertor studies

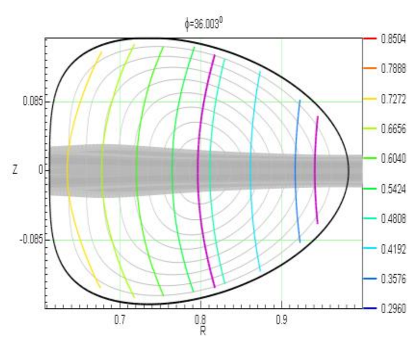
ECRH absorption modeling with TRAVIS* code



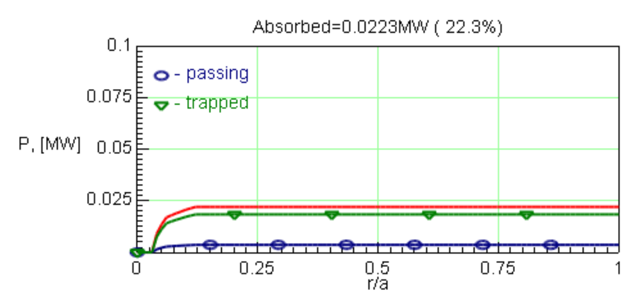


Top-port launch



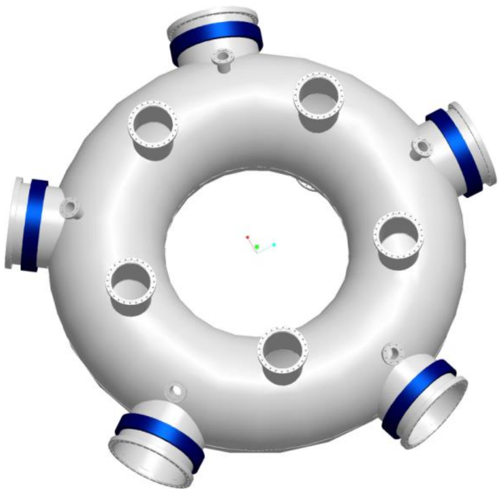


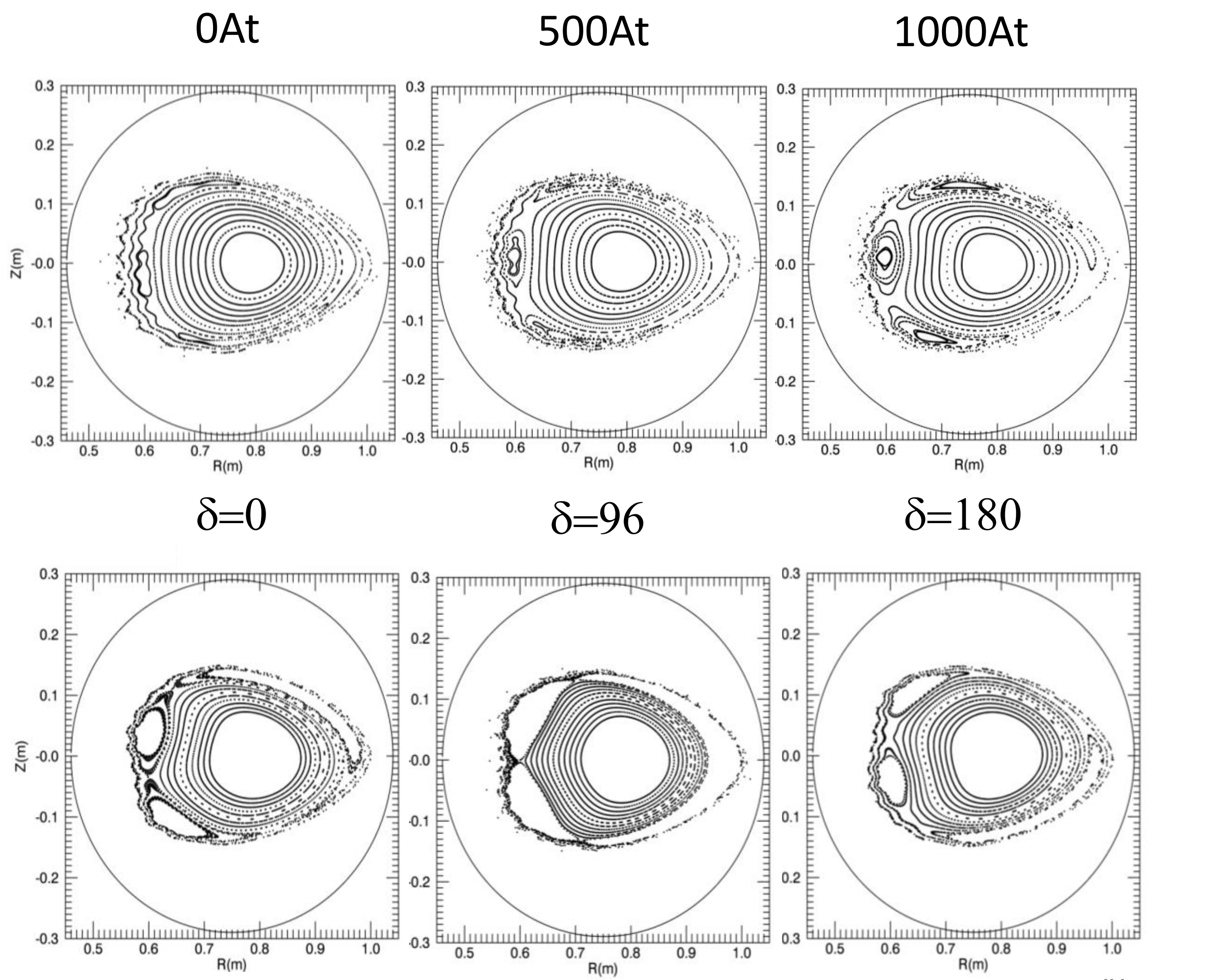
Side-port launch



*Marushchenko et al., *Comput. Phys. Commun*. **185**, 165 (2014)

Error Correction Coils can modify the amplitude and phase of magnetic islands





Divertor modeling has been started with EMC3-EIRENE* code

Outboard plate

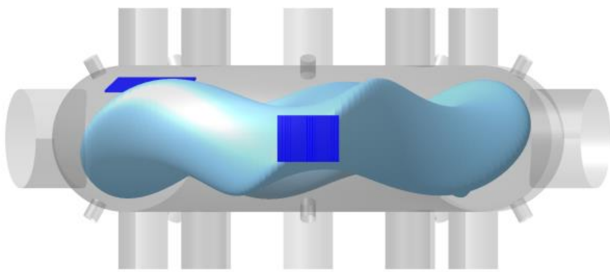
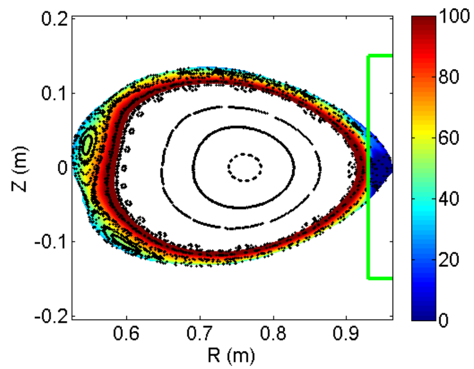
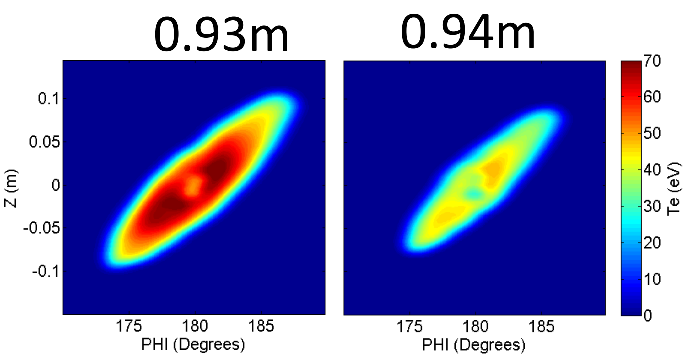
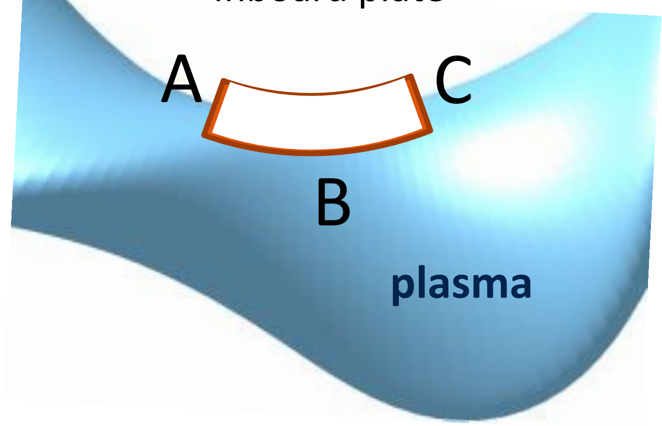


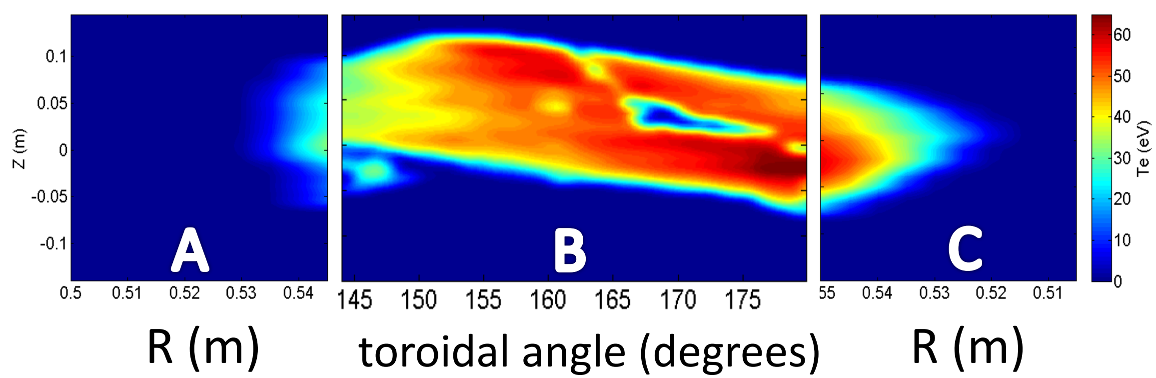
Plate temperature modeling





Inboard plate



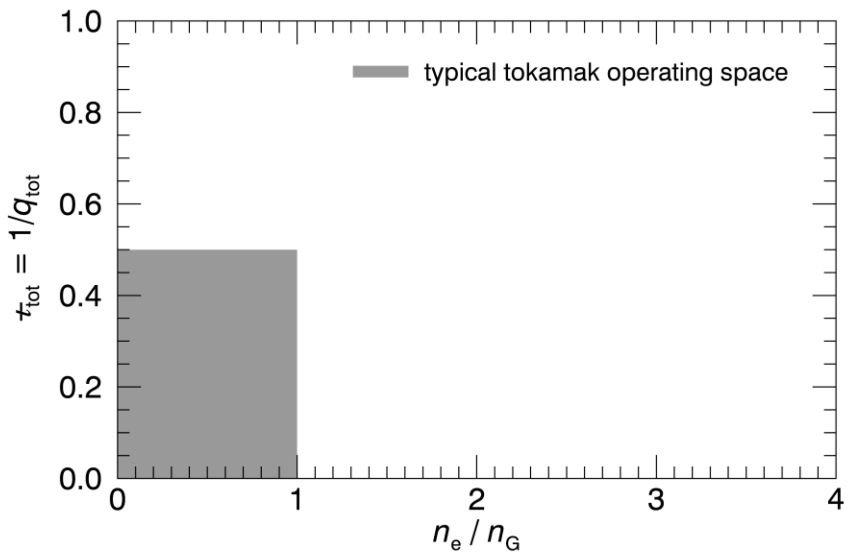


*Y. Feng, M. Kobayashi, T. Lunt, and D. Reiter, *PPCF*,**53** (2011) 024009

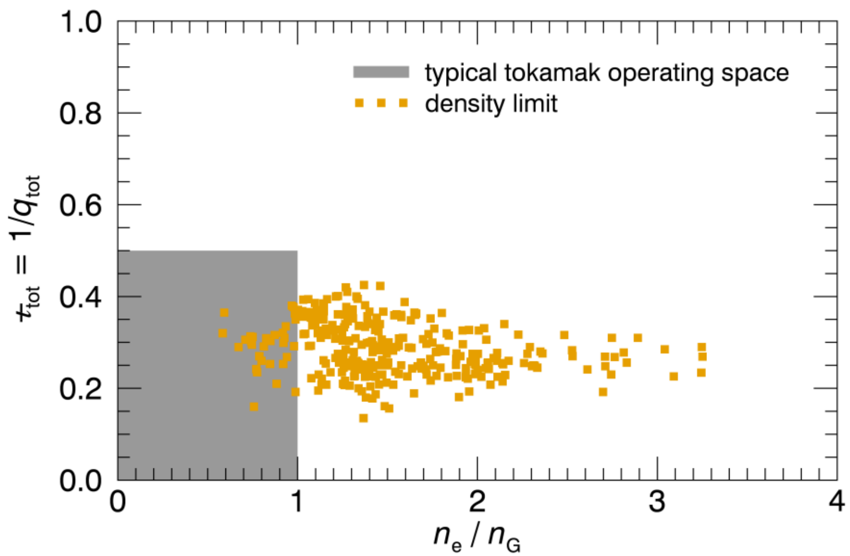
Summary

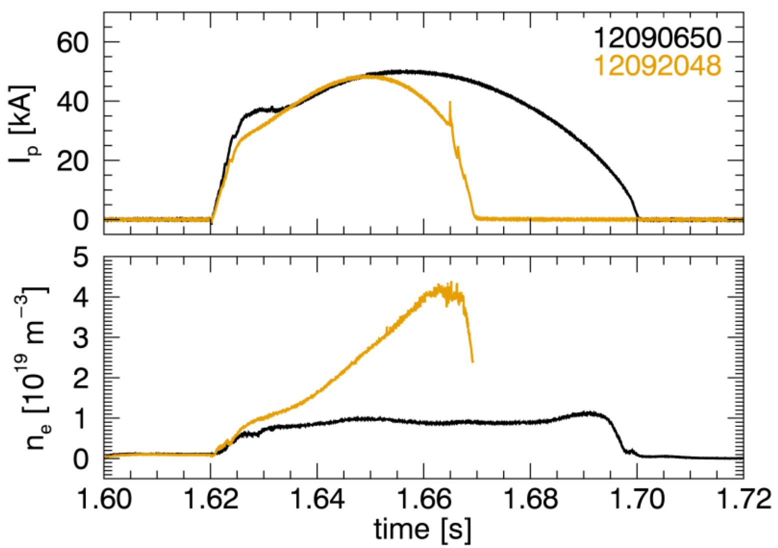
- Toroidal magnetic confinement is the leading candidate for a fusion energy power plant.
- The Compact Toroidal Hybrid (CTH) at Auburn University is a university scale experiment used to study the stability of magnetically confined, current-carrying plasmas.
- CTH studies show that 3D shaping on the order of 10% can increase the stability of VDEs, density limit, and low-q instabilities.
- Future work includes the addition of a 200 KW, 28 GHz gyrotron to give hotter plasmas for resonant and non-resonant divertor studies

Overview of CTH operational space and three types of disruptions observed



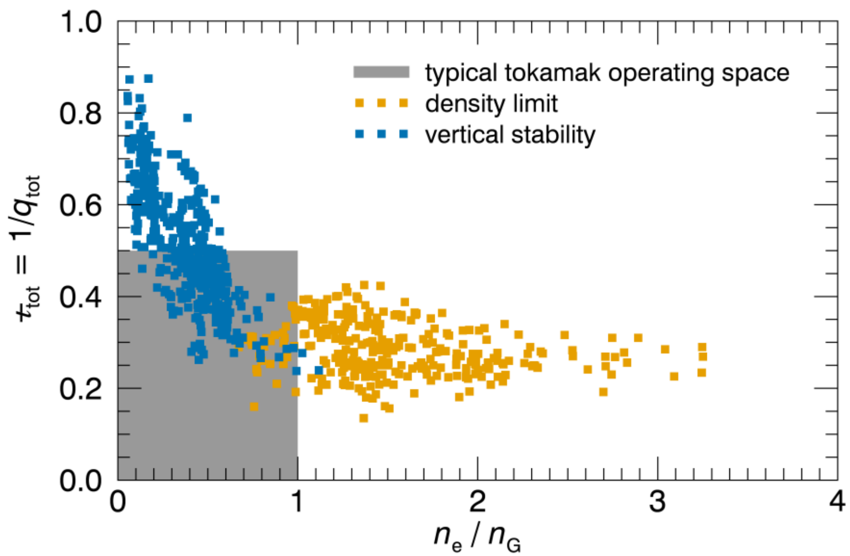
CTH can operate beyond the Greenwald density limit

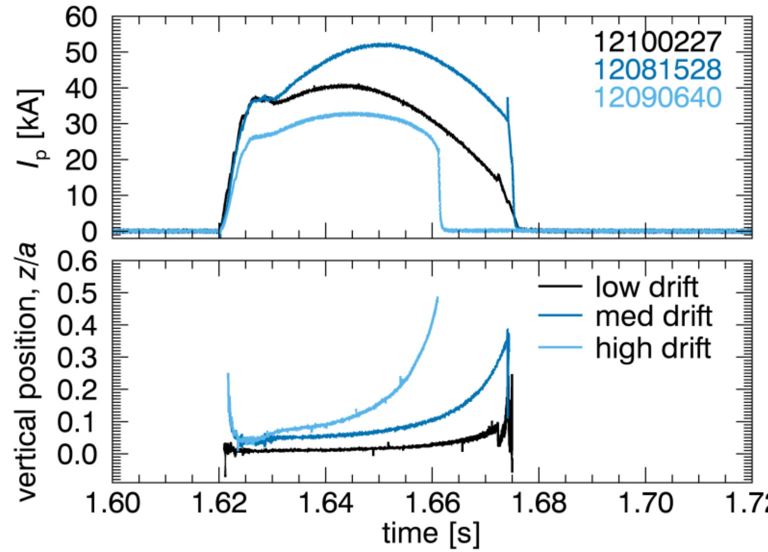




- Density-limit disruptions

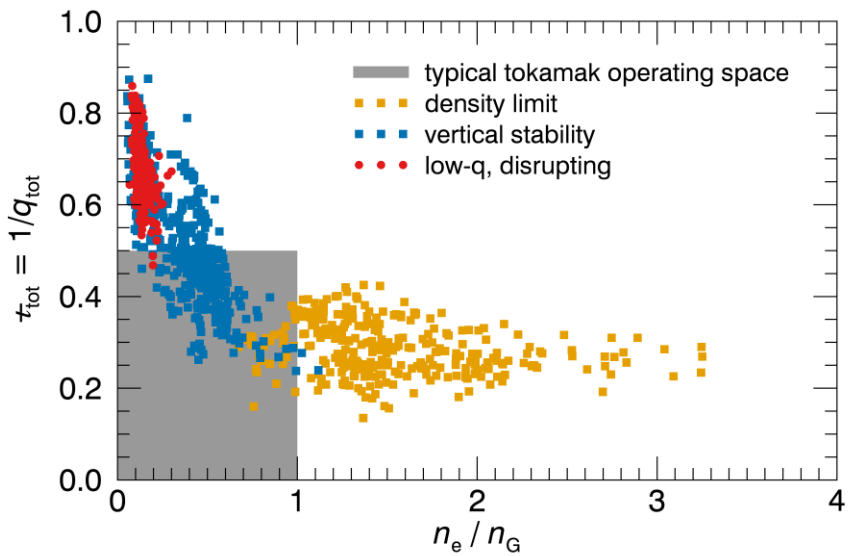
Vertically unstable plasmas can result in a disruption if uncompensated

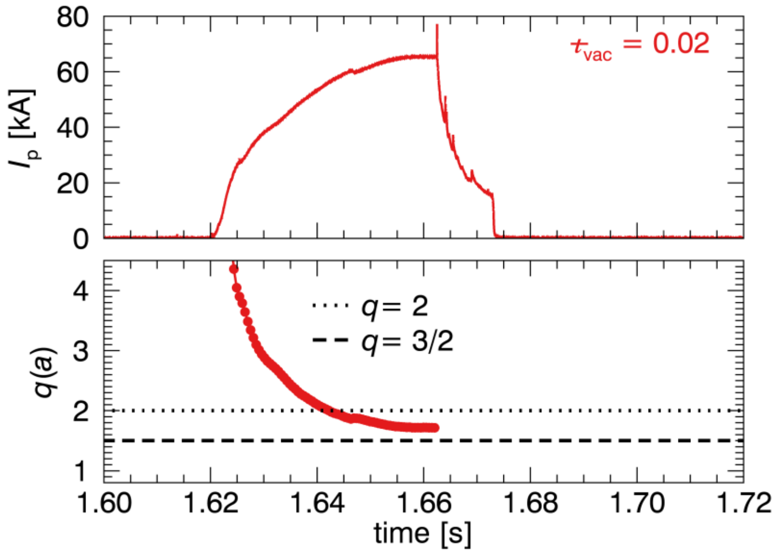




- Density limit disruptions
- Vertically unstable plasmas

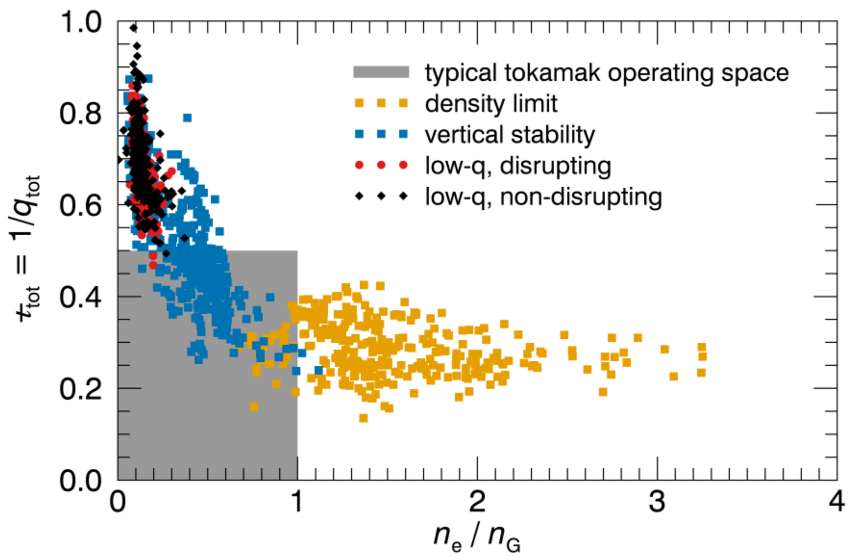
Low-q disruptions can occur when CTH operates with $q(a) < 2$

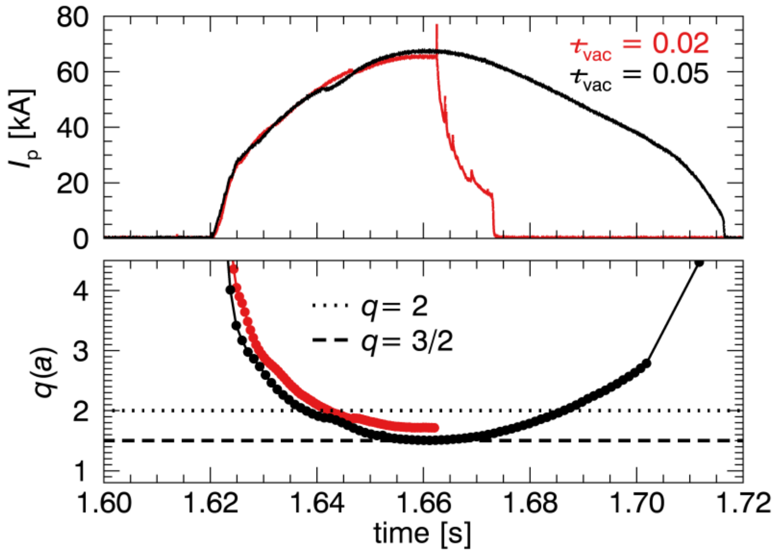




- Density limit disruptions
- Vertically unstable plasmas
- Low-q disruptions

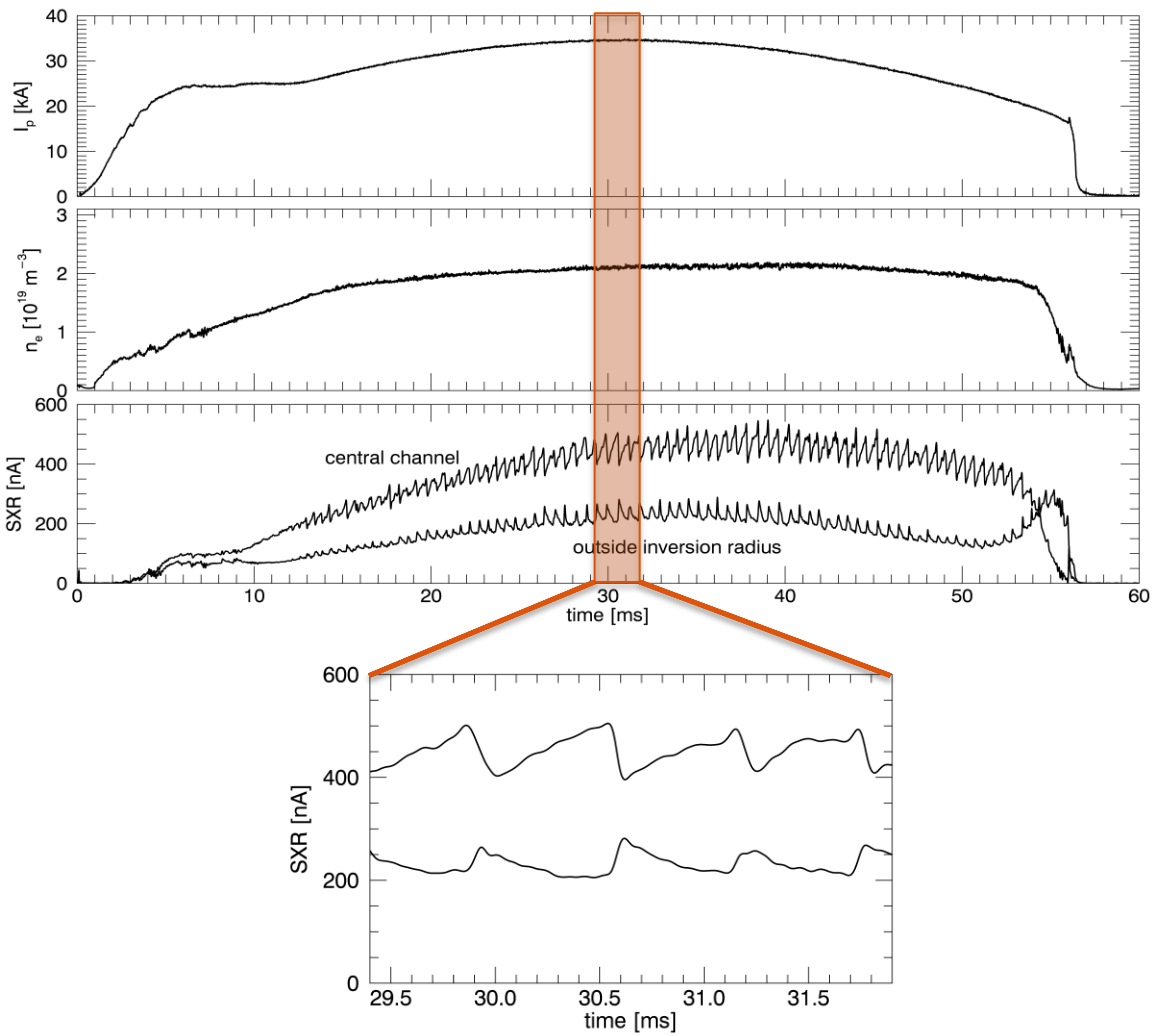
CTH can operate beyond the $q(a)$ = 2 current limit, with a slight increase in ι_{vac}

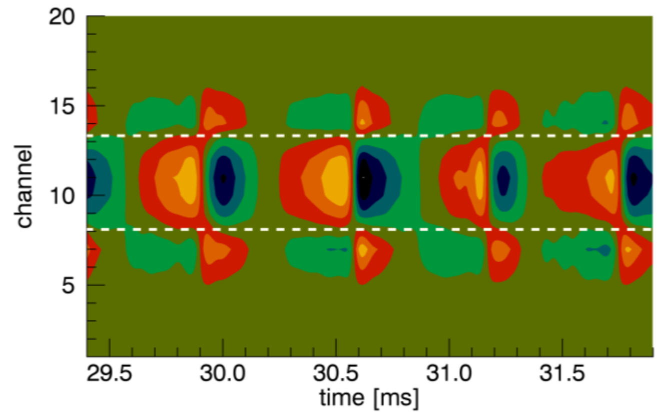


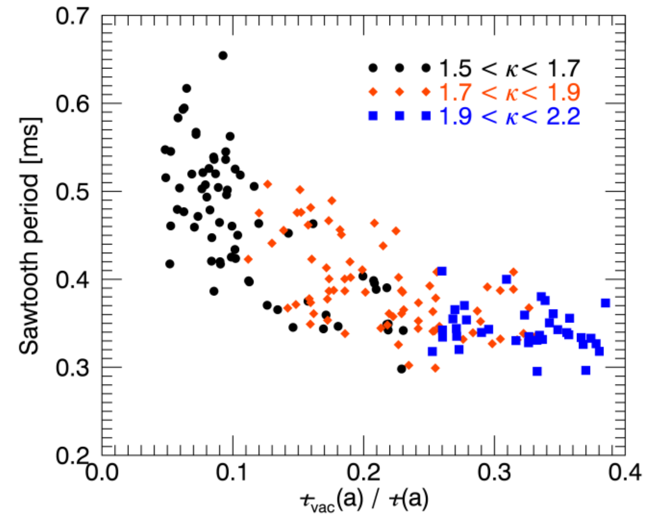


- Density limit disruptions
- Vertically unstable plasmas
- Low-q disruptions

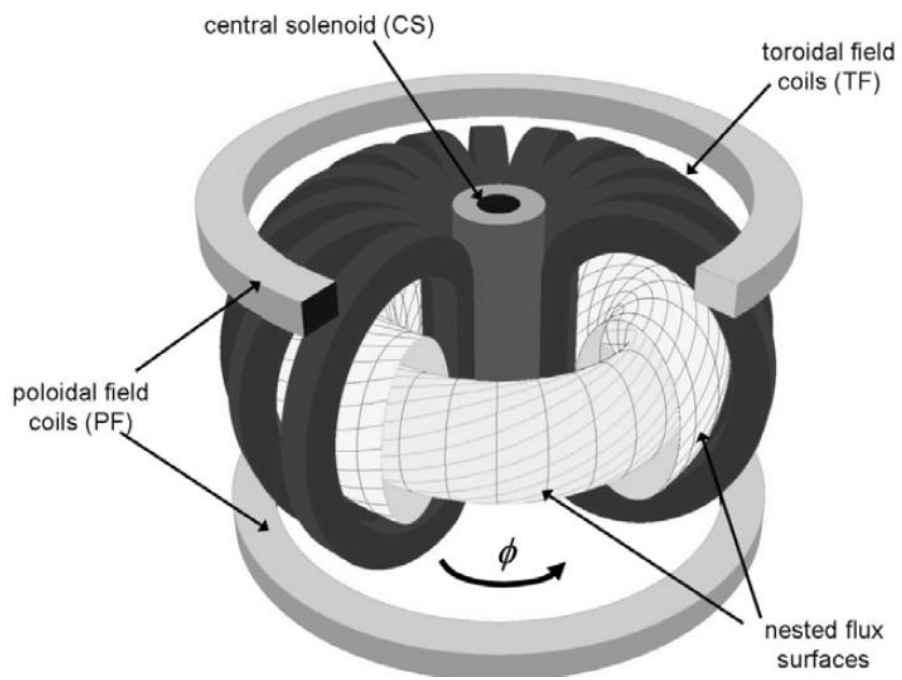
Sawtooth oscillations observed on CTH exhibit behavior similar to that of axisymmetric tokamaks







In the tokamak closed magnetic flux surfaces are generated with inductively driven plasma current



- The poloidal field is generated by the inductively driven plasma current
- In limiting cylindrical case edge rotational transform:

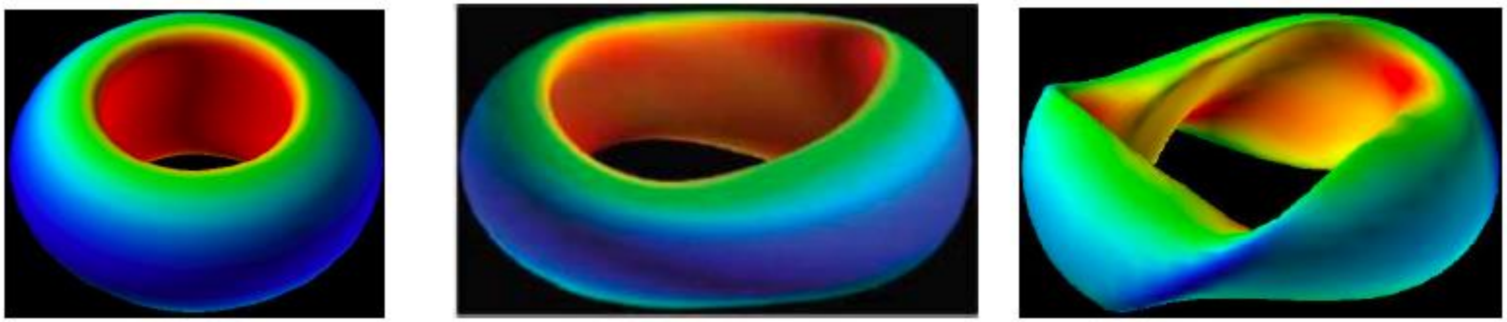
$$\iota(a) = \frac{\mu_0 R_0 I}{2\pi a^2 B_z(a)} = \frac{1}{q(a)}$$

- Current driven MHD instabilities limit the amount of driven plasma current
- Can lead to uncontrolled loss of confinement: disruptions

Fusion Physics, IAEA

Present day tokamaks use 3D magnetic fields to improve control and performance

- Small amounts of 3D fields are used for a variety of purposes on present day tokamaks with $B_{3D}/B_0 \sim 10^{-3}$
  - Resistive wall modes, ELM control, error field correction
- Disruptions do not routinely occur in (net) current free stellarators



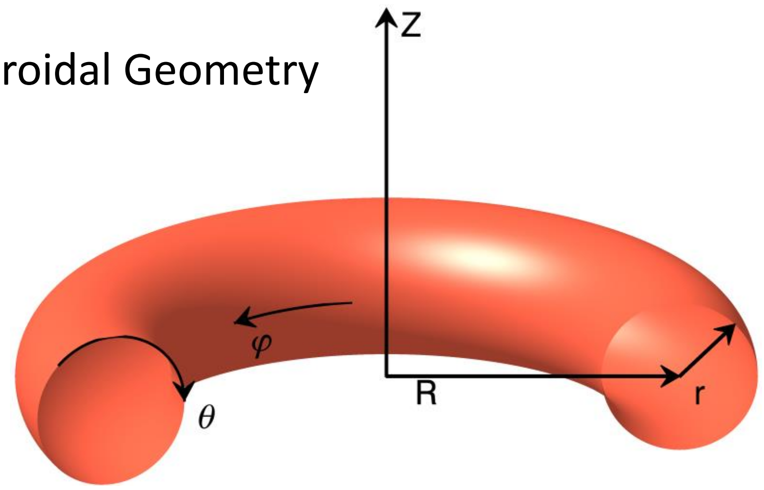
(A. Boozer, Plasma Phys. Control. Fusion. 2008)

- Question: What is the effect of higher levels of 3D magnetic shaping, $B_{3D}/B_0 \sim 0.1$, on tokamak instabilities and disruptions?

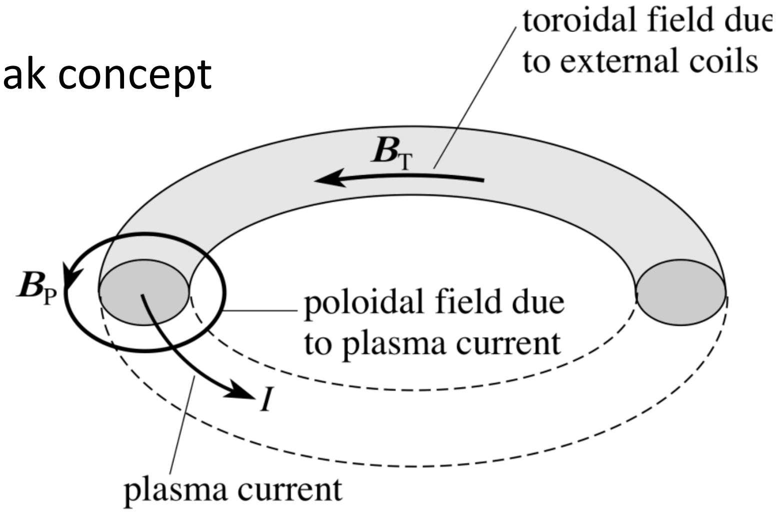
Helical magnetic fields are required for confinement in toroidal devices

- A pure toroidal field will not confine a plasma.
  - $\boldsymbol{B} \times \nabla B$ and $\boldsymbol{R_c} \times \boldsymbol{B}$
  - $\boldsymbol{E} \times \boldsymbol{B}$
- Toroidal plasmas are confined with a combination of toroidal and poloidal magnetic fields.

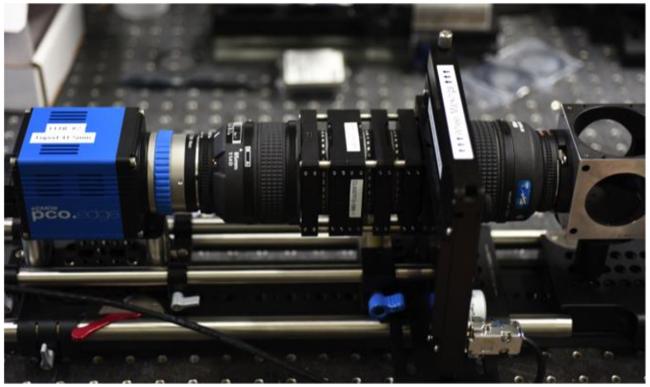
Toroidal Geometry

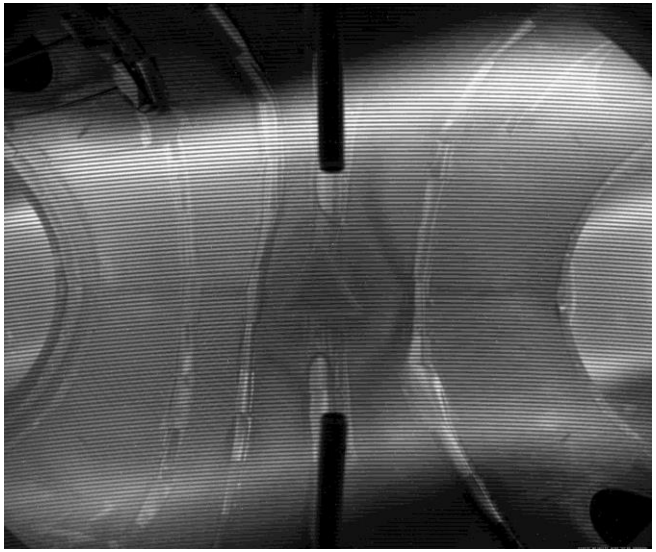


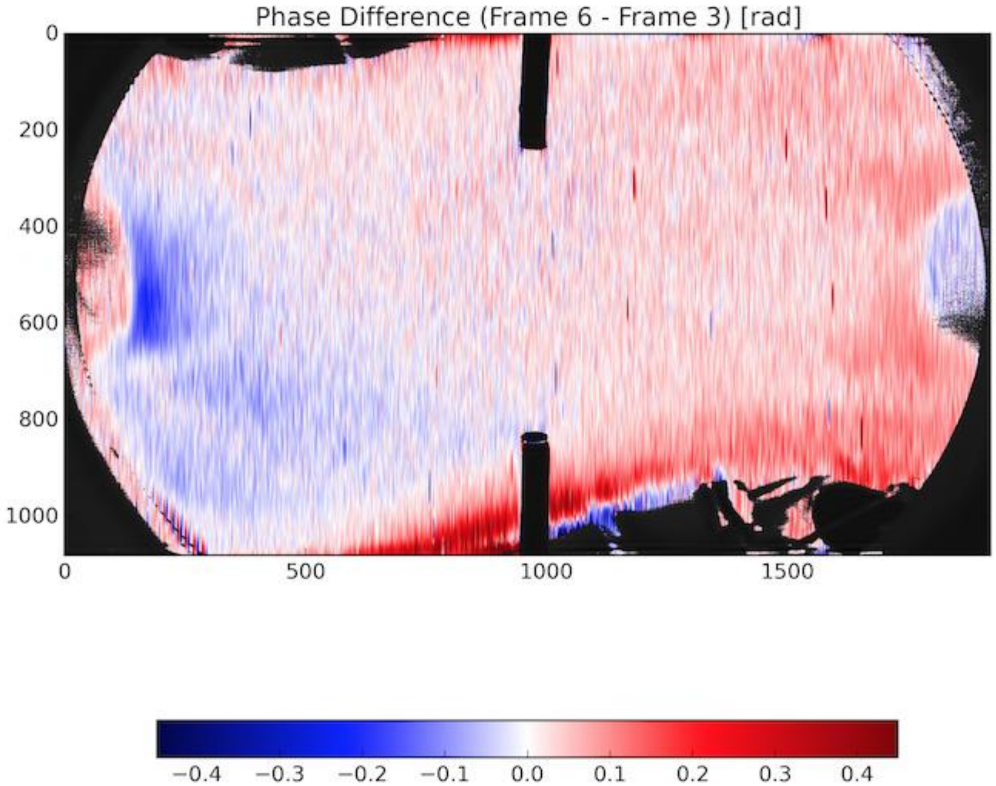
Tokamak concept



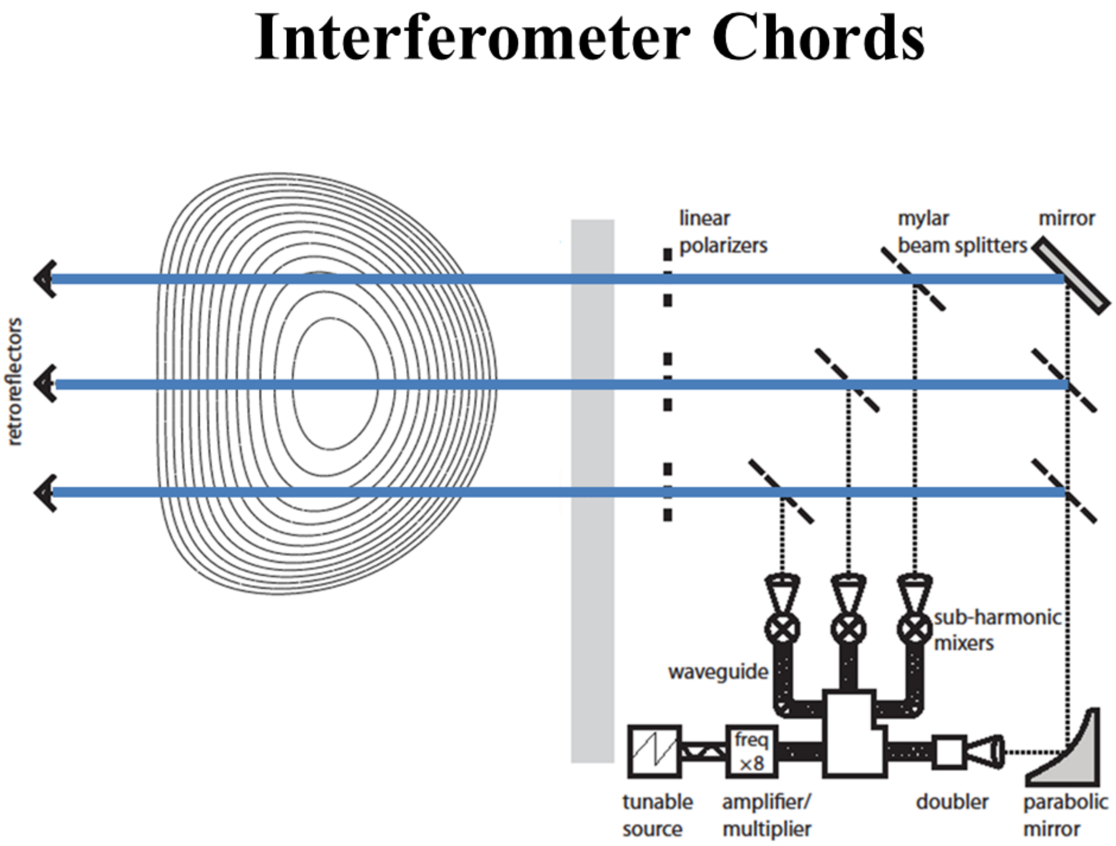
Coherence Imaging is under development



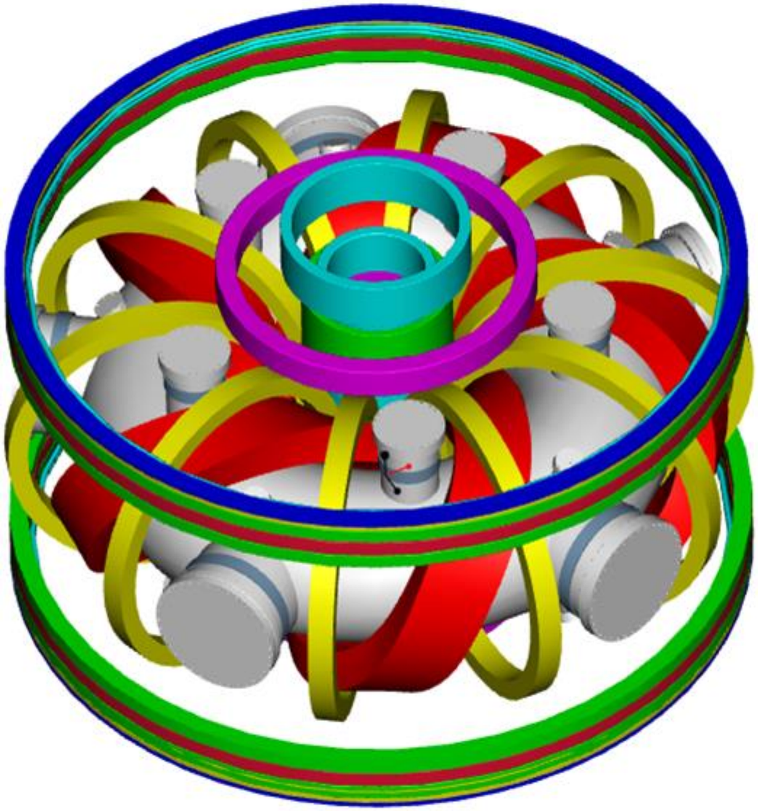


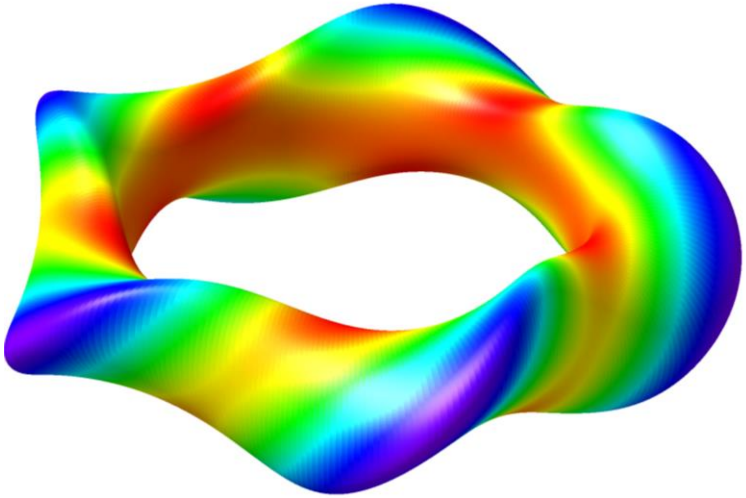


A three chord, 1mm interferometer is used to measure electron density

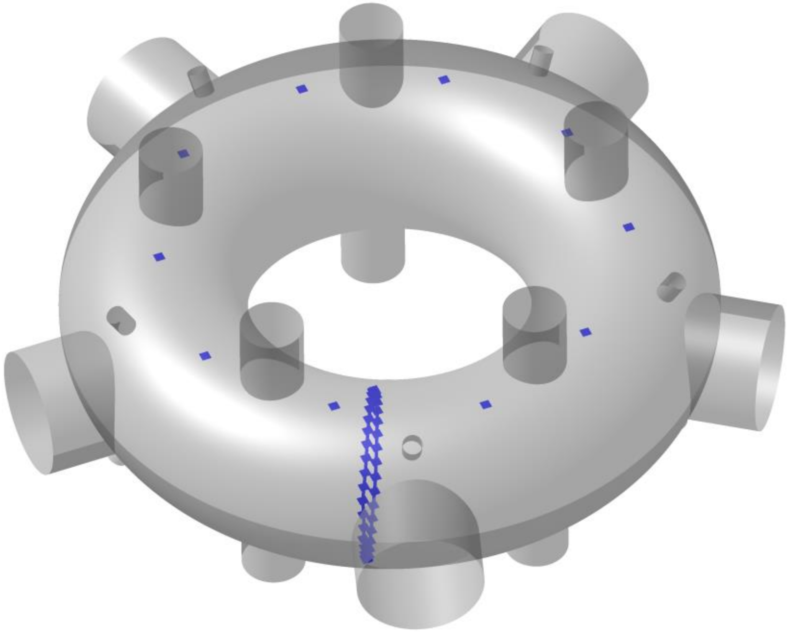


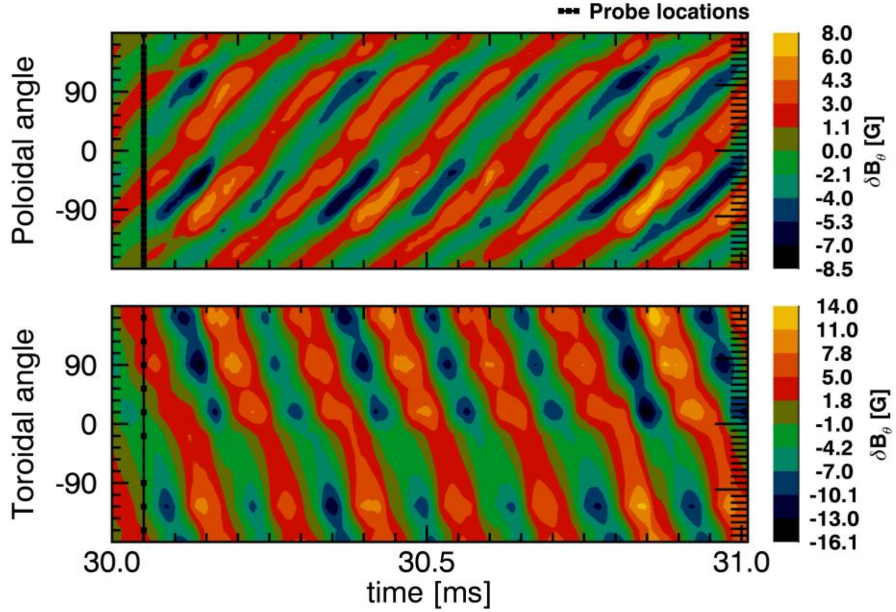
The Compact Toroidal Hybrid





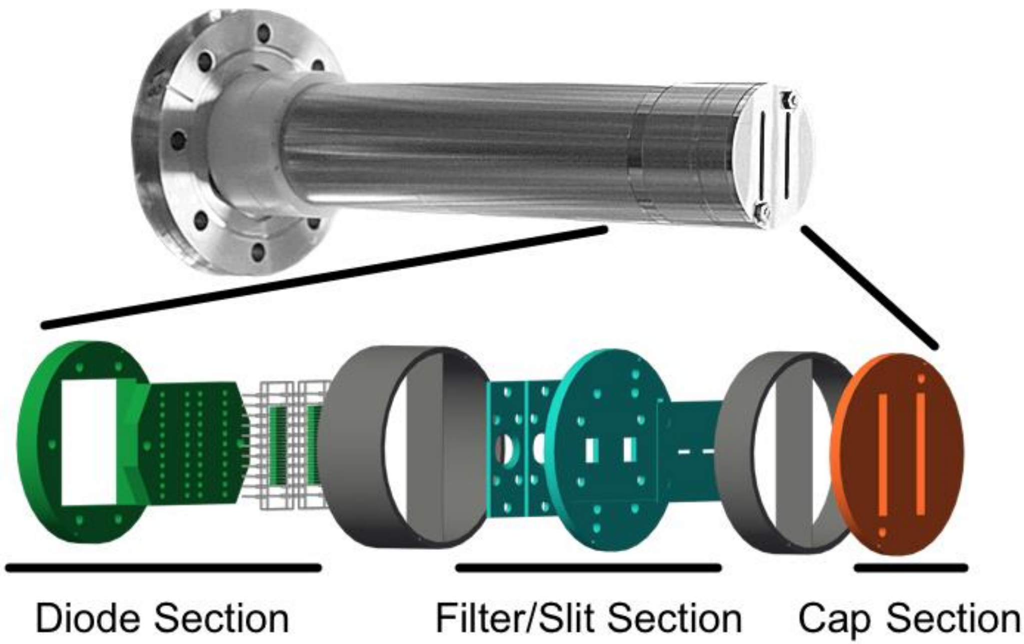
The structure of MHD modes is analyzed using one poloidal array and one toroidal array of B-dot probes



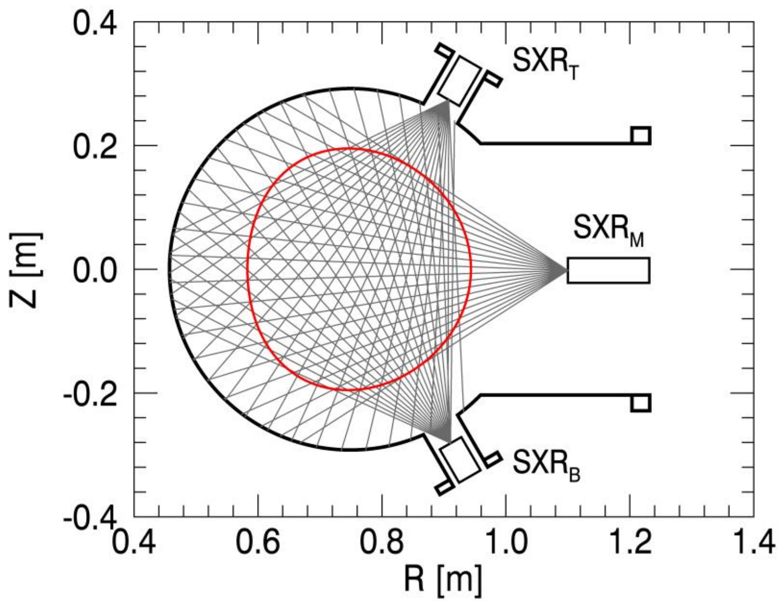


Soft X-ray (SXR) arrays

Dual Energy Cameras



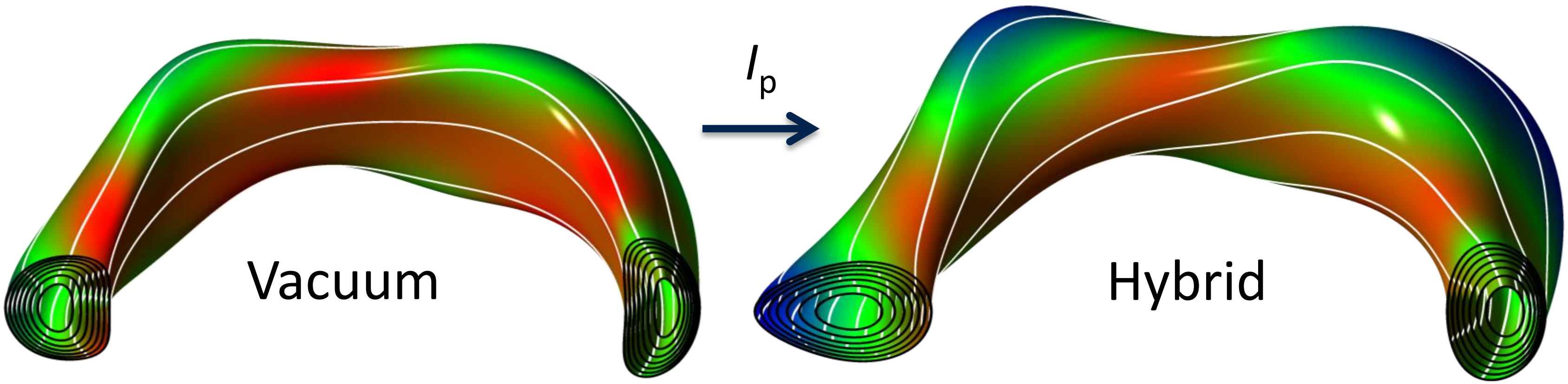
SXR Viewing Chords



J. L. Herfindal, et al., *Rev. Sci. Instrum.* **85** 11D850 (2014)

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

- Plasma current strongly modifies the CTH equilibrium



- V3FIT[1] finds an MHD equilibrium most consistent with data, $\boldsymbol{d}$
- CTH uses VMEC[2] to model the equilibrium with parameters, $\boldsymbol{p}$

$$\chi^2 = \sum_i \left(\frac{S_i{}^o(\boldsymbol{d}) - S_i{}^m(\boldsymbol{p})}{\sigma_i{}^S} \right)^2$$

[1]J.D. Hanson et al., *Nucl. Fus.*, 2009, [2]S.P. Hirshman et al., *Comp. Phys. Comm*. 1986