Low edge safety factor disruptions in the Compact Toroidal Hybrid: Operation in the low-q regime, passive disruption avoidance and the nature of MHD precursors

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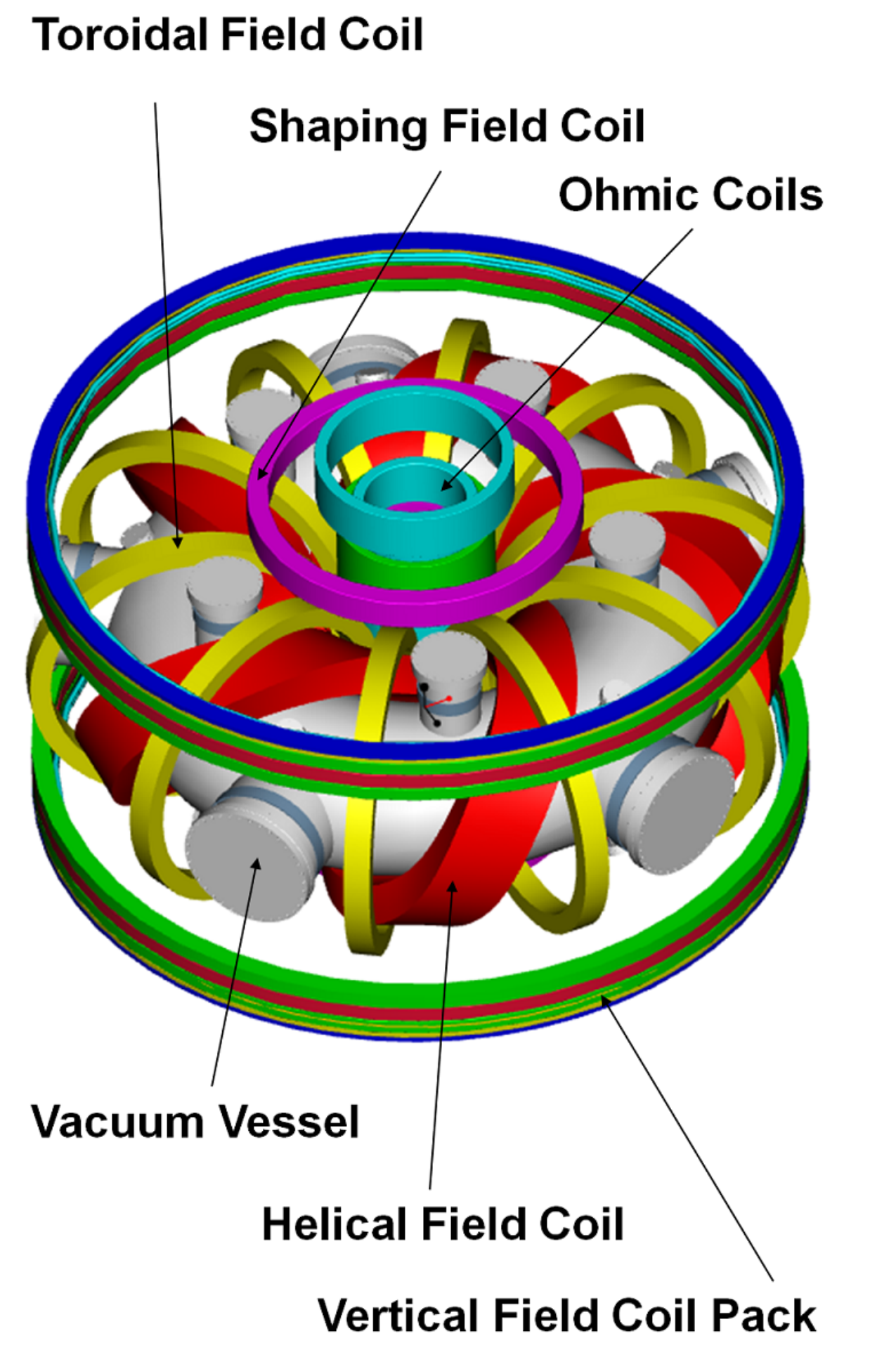
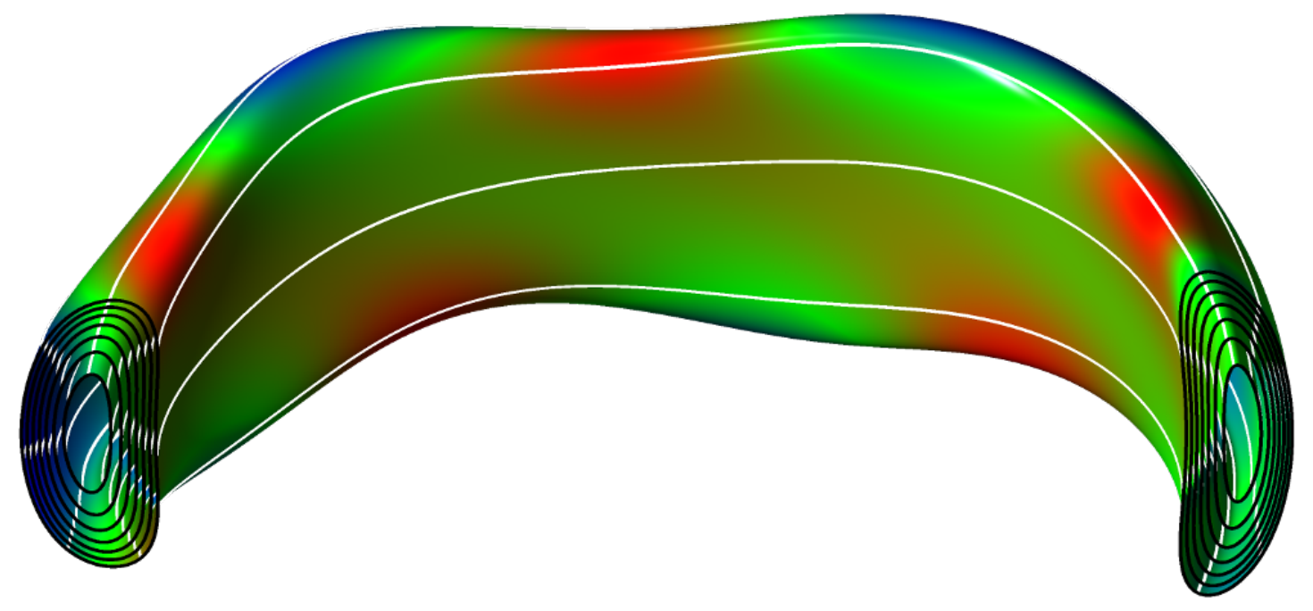
Compact Toroidal Hybrid

The Compact Toroidal Hybrid (CTH) is a torsatron-tokamak hybrid with a helical field coil and vertical field coils to establish a stellarator equilibrium, while an ohmic coil induces plasma current.



A feature of the CTH device is the ability to adjust the vacuum rotational transform, ι_{vac} ($\iota = \frac{1}{q}$), by varying the ratio of current in the helical and toroidal field coils.

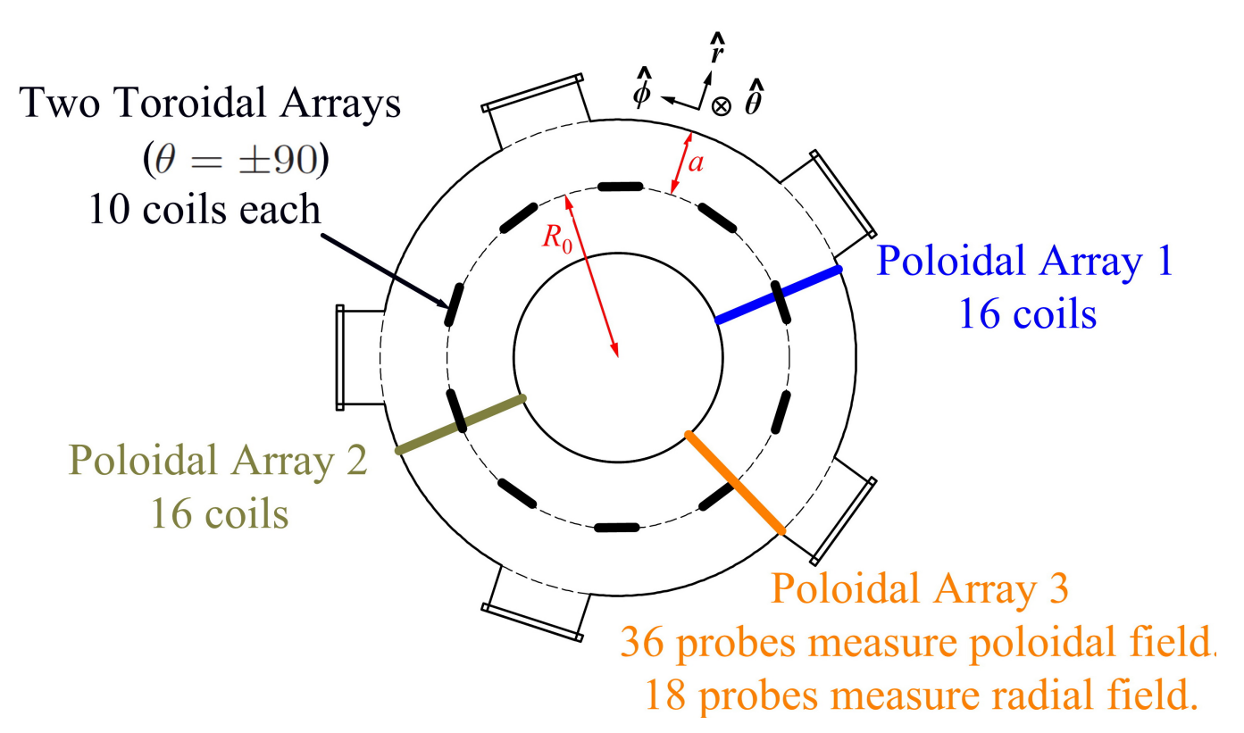


Vacuum flux surfaces generated by external stellarator coils with $\iota_{vac} = 0.05$. White lines are magnetic field lines, and red color represents high magnetic field strength while blue is low. The helical modulation of magnetic field strength is about 0.15 T with $\langle |B| \rangle = 0.5$ T.

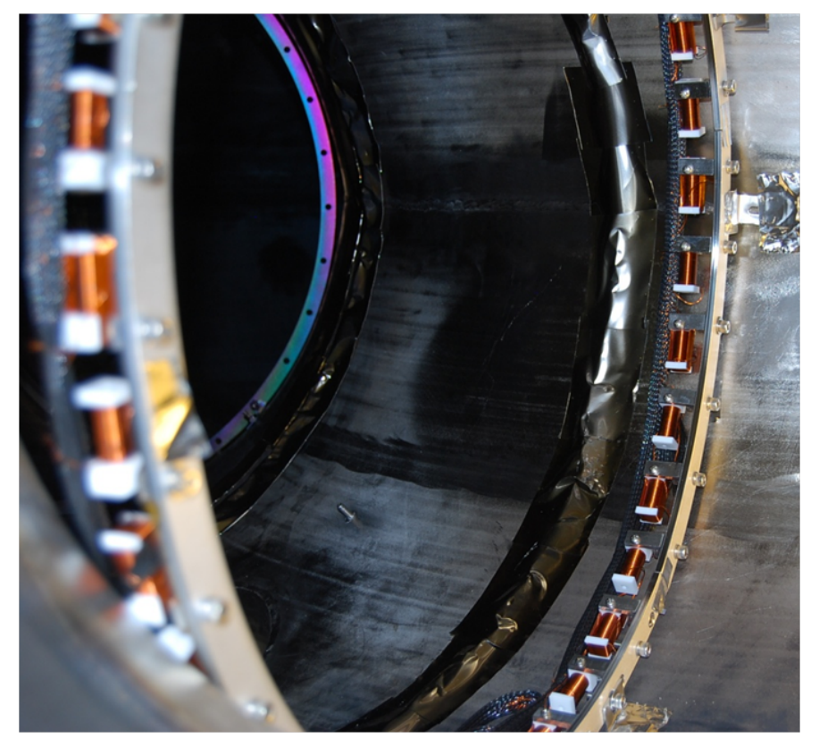
CTH Parameters

$R_0 = 0.75$ m	$a_v = 0.29$ m	$a_{plasma} = 0.2$ m
$B_0 \leq 0.7$ T	$P_{ECRH} \leq 30$ kW	$P_{OH} \sim 200$ kW
$I_p \leq 80$ kA	$n_e \leq 5 \times 10^{19}$ m^{-3}	$T_e \leq 200$ eV
$\iota_{vac}(a) \sim 0.02 - 0.3$	$\beta \leq 0.5\%$	Discharge duration$\leq$ 0.1 s

Magnetic fluctuations detected with multiple arrays of B_θ pickup coils

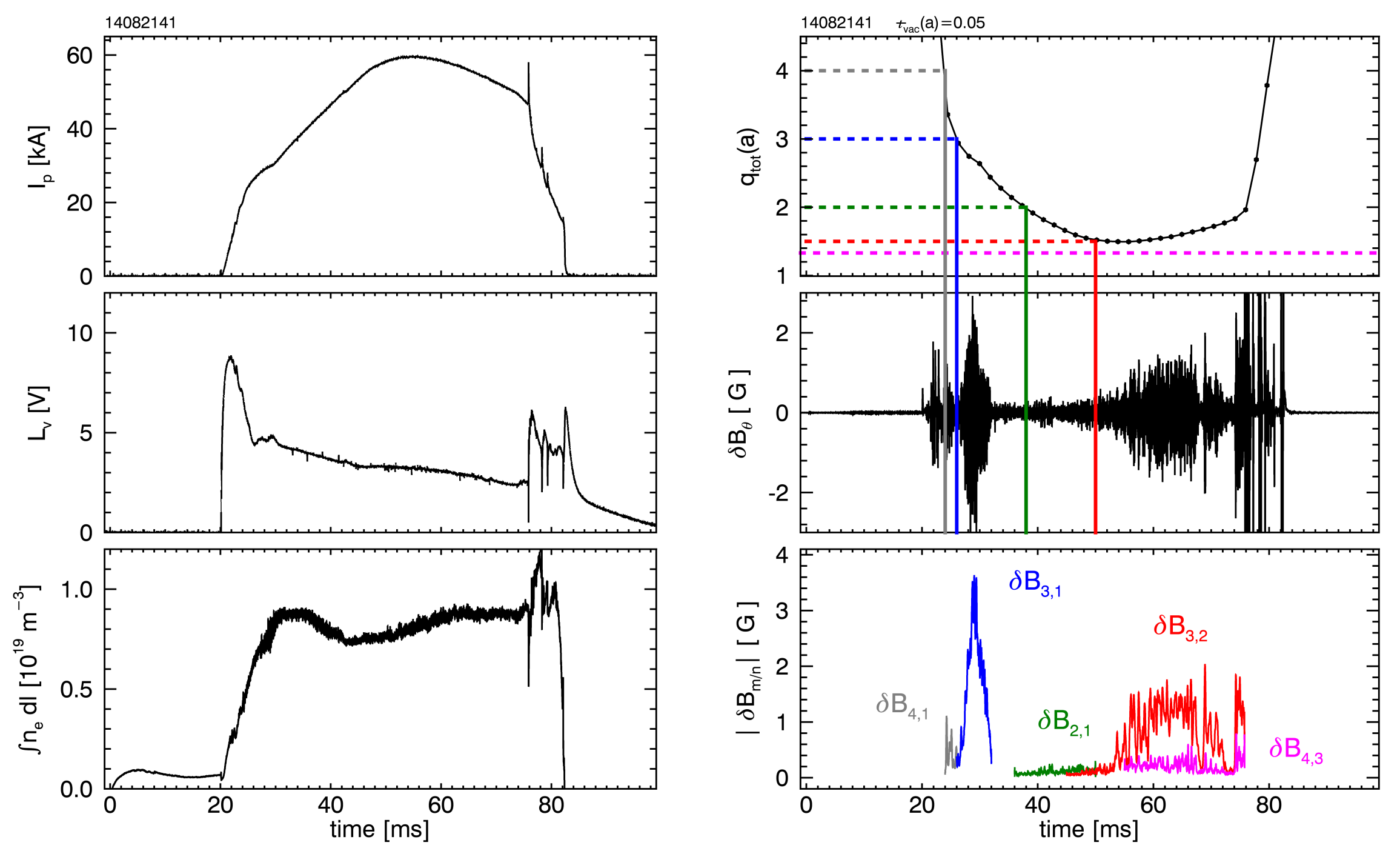


Poloidal and toroidal arrays of pickup coils are used to determine the poloidal (m) and toroidal mode numbers (n).



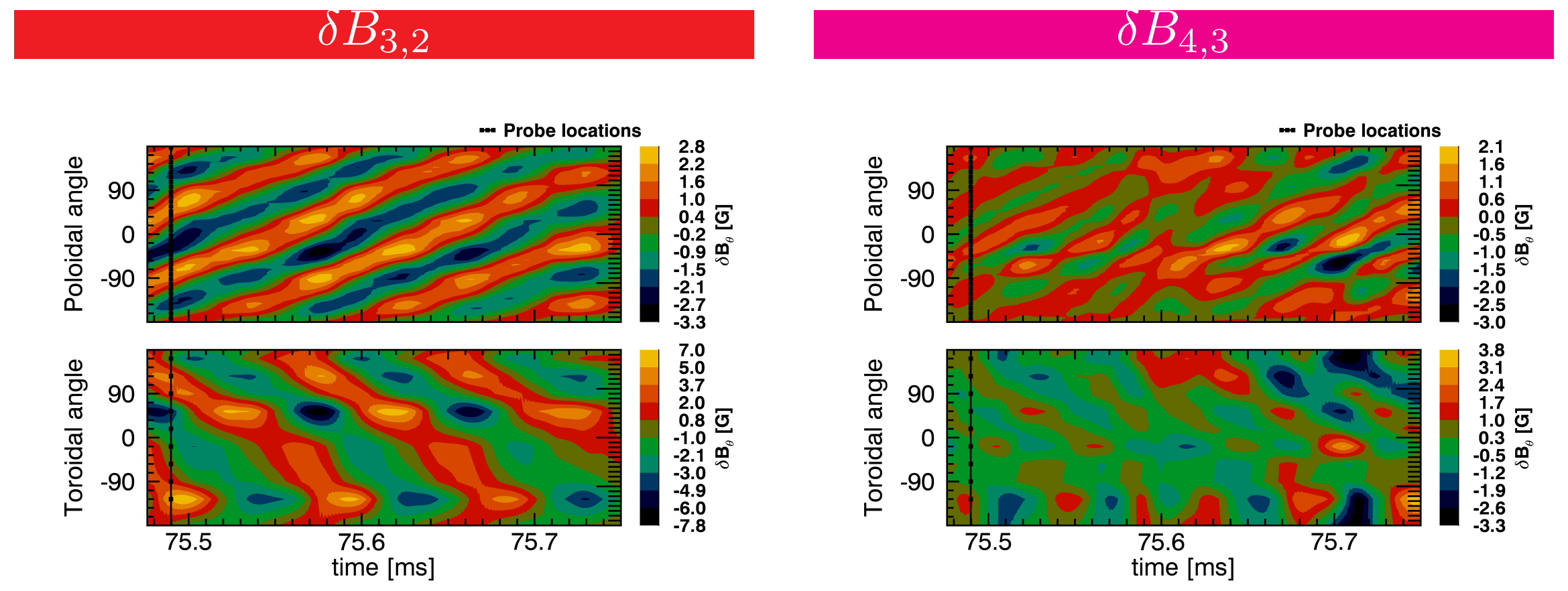
Picture of one of the poloidal arrays installed inside the CTH vacuum chamber is shown here. It has 36 probes that measure the fluctuations in poloidal field.

Low-$q(a)$ disruptions observed $q(a) < 2$



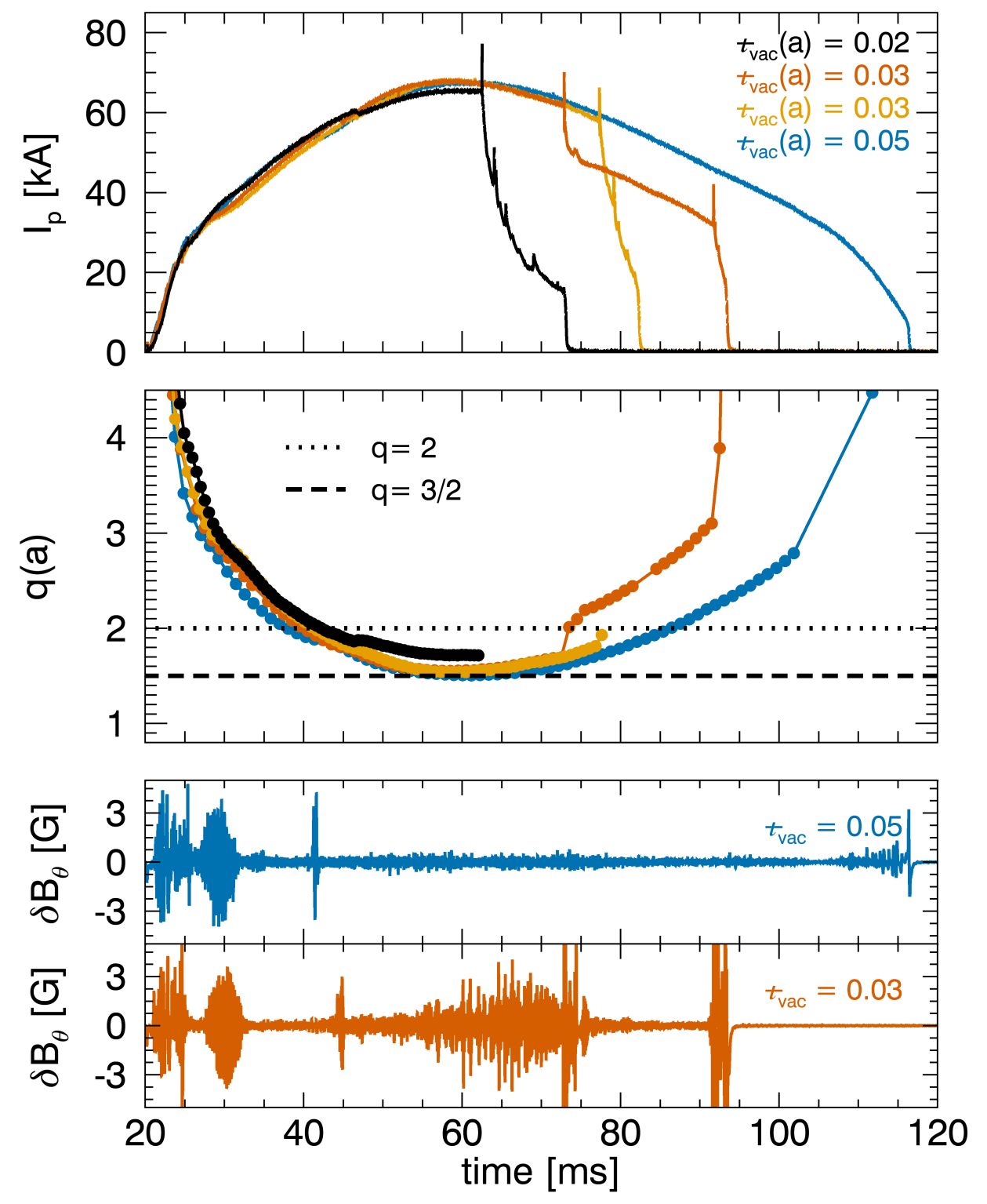
- Disruption preceded with a positive spike in I_p and negative spike in V_ℓ.
- **q(a)<2 at disruption, m/n=2/1 activity is saturated and small in amplitude.**
- As the plasma current evolves, observed structure of MHD activity corresponds to rational values of $q(a)$.
- **3/2 and 4/3 modes observed are precursors to the disruption. Non-sawtoothing 1/1 mode observed on SXR signals.**

3/2 and 4/3 modes grow prior to disruption



- Biorthogonal decomposition [5] is used to separate 3/2 and 4/3 modes from total fluctuations in δB_θ.
- Frequency of 3/2 mode, $f_{3/2} \sim 10 - 12$ kHz and $f_{4/3} \sim 18 - 19$ kHz .

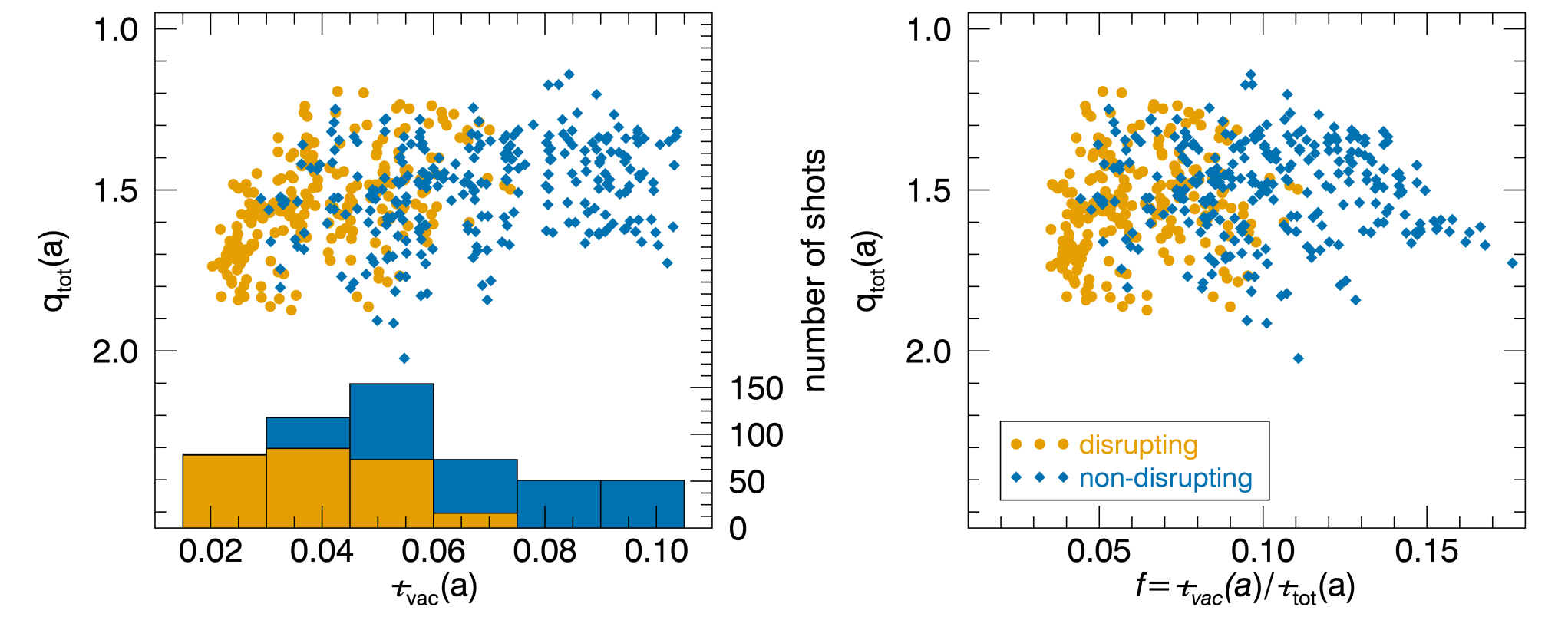
Disruptivity changes with addition of ι_{vac}



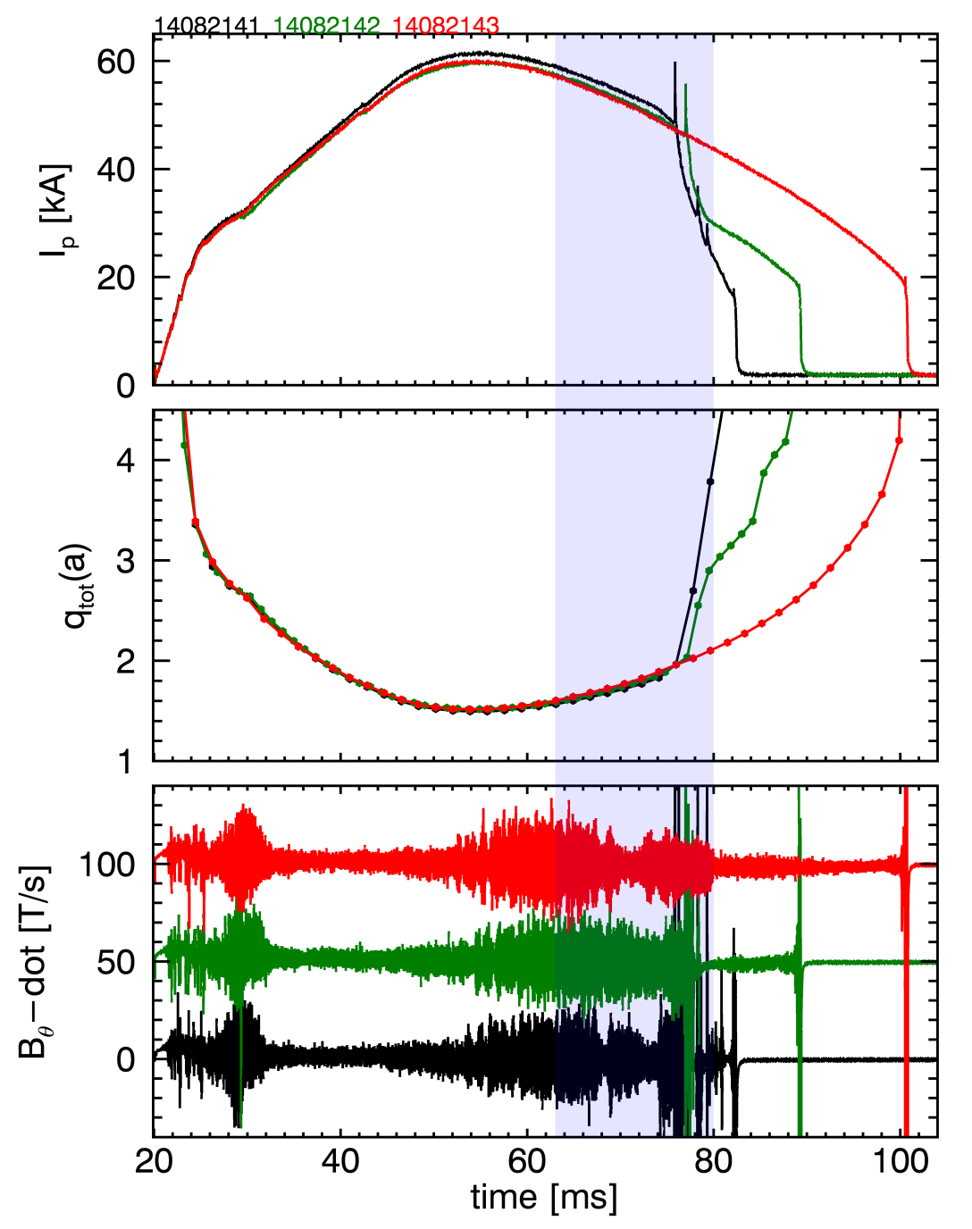
- ι_{vacuum} changed by changing the ratio of currents in helical field coil (HF) and the toroidal field coil(TF).
- The figure shows discharges with different values of vacuum transform, but with similar evolution of the total plasma current.
- Total rotational transform, $\iota_{tot} = \iota_{vacuum} + \iota_{current} = \frac{1}{q}$, is maintained approximately constant.

Disruptions suppressed for $f \gtrsim 0.1$

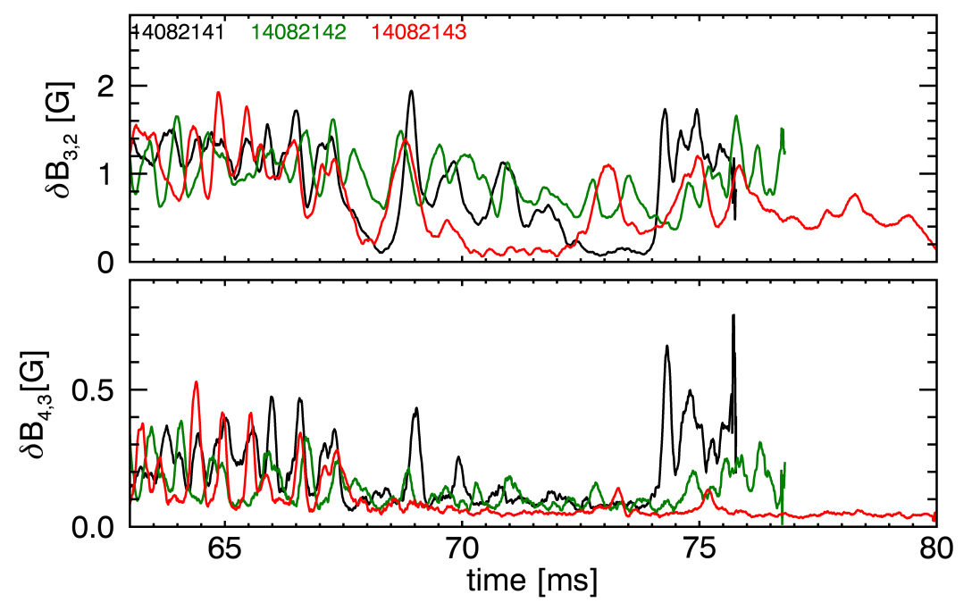
- Fractional transform is defined as $f = \iota_{vacuum}/\iota_{tot}$, with ι_{tot} computed at peak plasma current.
- About 500 shots are taken for a range of values of$\iota_{vac}(a)$ and ι_{tot}.
- Disruptions are suppressed as $\iota_{vac}(a)$ is raised to 0.07.



m/n=3/2 and 4/3 modes are dominant disruption precursors



Comparison of shots at fixed value of $\iota_{vac}(a) = 0.05$, $f \sim 0.3$



- Three shots have similar evolution of $q(a)$ and I_p.
- Growing 3/2 and 4/3 modes lead to a disruption in two shots. For third shot, 3/2 and 4/3 remain small and disruption is not observed.

Comments

- CTH operates beyond the traditional tokamak limit of q(a)>2. Low-q(a) disruptions on CTH are driven by 3/2 and 4/3 modes.
- A threshold for disruption suppression is observed at a modest fractional transform of about 0.1
- Hybrid machines in past have observed disruption suppression of the 2/1 mode at levels of $\iota_{vac} \sim 0.14$[6].
- The conjecture to explain the suppression there was that the addition of vacuum transform shifts the location of the rational surface to a region of less steep current gradient and hence increased stability.
- We think that a similar mechanism might be responsible for disruption suppression in CTH. Knowledge of current profile for CTH will give a clear picture the mechanism.

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References

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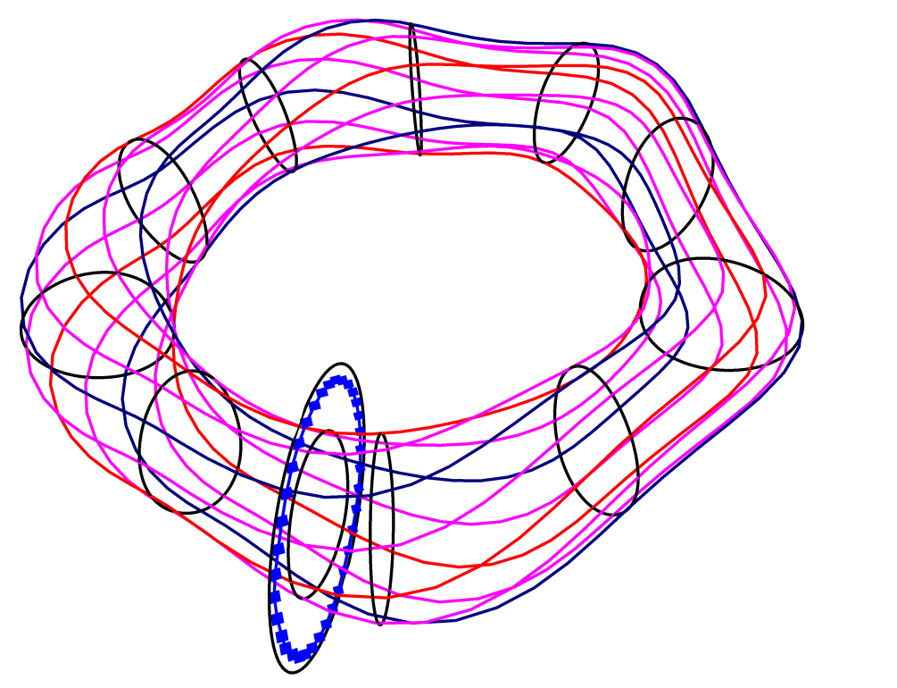
Modeling MHD fluctuations in CTH

- Current driven long wavelength modes have constant phase along a field line $\vec{k} \cdot \vec{B_0} = 0$. Mode structure is "flute-like" with $\vec{k} \perp \vec{B_0}$.
- In cylindrical plasma, this implies that perturbed currents are parallel to the equilibrium magnetic field lines $\left(\nabla \times \delta\vec{B}\right) \cdot \hat{r} = 0 \implies \delta\vec{j}_{\parallel}$.
- To understand CTH 3D mode structure, we use V3FIT [2] reconstructions to define field aligned perturbed current paths and fit for measured fluctuating fields.

Observed MHD modes modeled as current filaments on rational surface

$$\begin{aligned} \text{Model signal:} \quad S_i^M &= \textstyle\sum_{j=0}^{N_f} M_{ij} I_j \\ \text{Filament current model:} \quad I_j &= I_0 \ \sin(m\theta_j + \delta) \\ \text{Fitting observed sig. } S_i^O: \quad \chi^2 &= \textstyle\sum_{i=0}^{N_D} \left[\frac{S_i^M - S_i^O}{\sigma_i}\right]^2 \end{aligned}$$

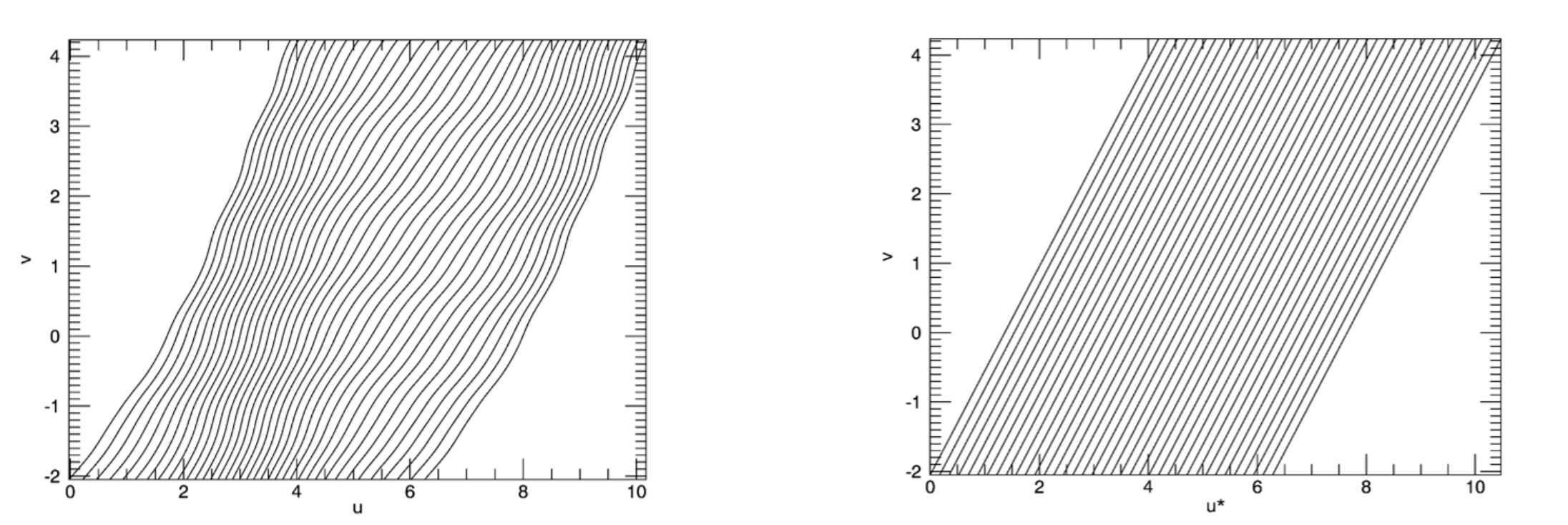


- Current filaments on rational surface with $\iota = 2/3$.
- Rational surface at half and full periods in CTH are shown. Poloidal array of B-dot probes is shown in blue.

Current filaments are uniformly spaced in straight field line coordinates

Standard VMEC coordinates

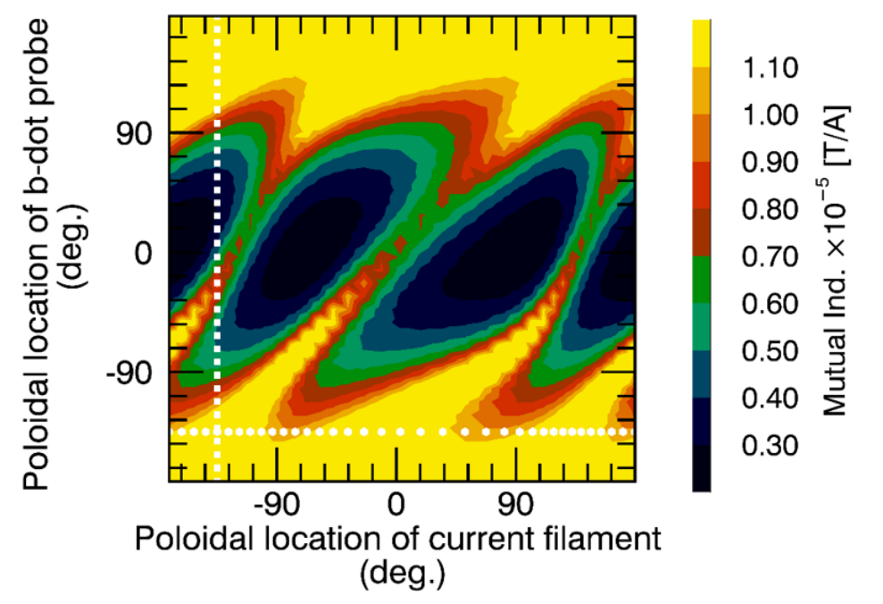
Straight field line coordinates



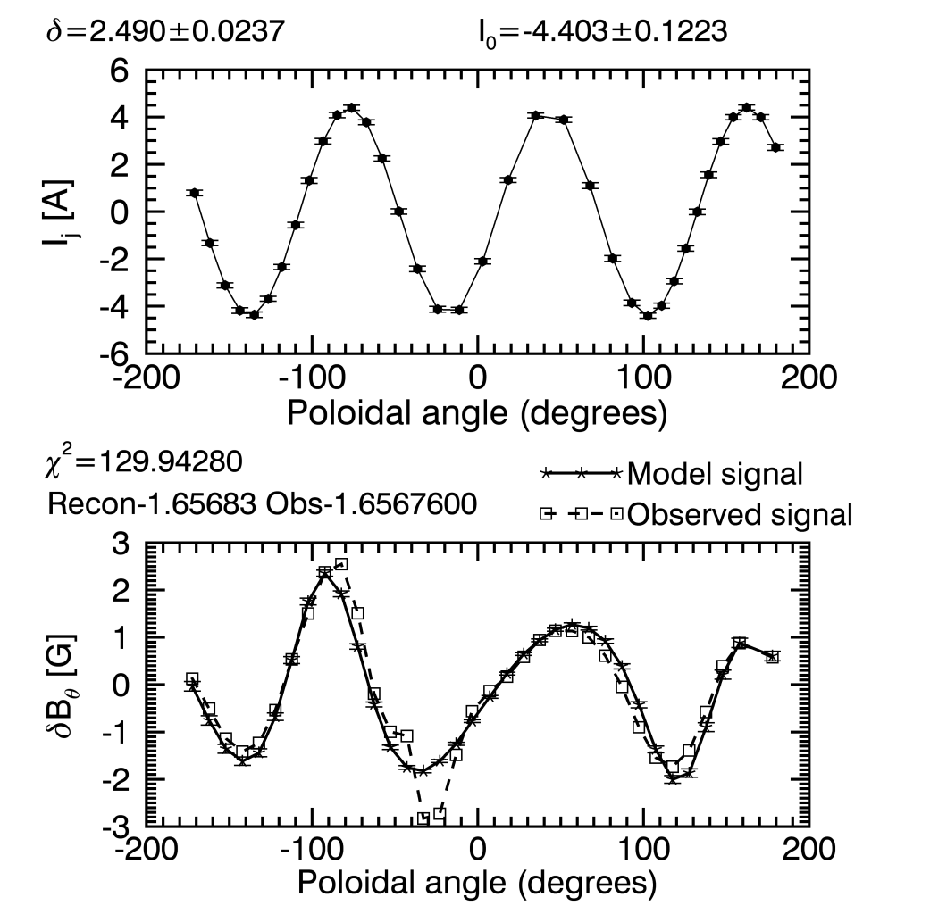
$u^* = u + \lambda(s, u, v)$
$\lambda = \sum \lambda_{mnc} \sin(mu - nv)$

$u^* = \iota(s) \cdot v + u_0^*$

Fluctations observed by poloidal array used to model current in filaments



- Mutual inductances, M_{ij}, between poloidal array of B-dot probes and filaments computed with V3RFUN code [3]



- Current in filaments, I_j, obtained by fitting amplitude and phase as free parameters of the current model.
- **Model signals reproduce the phase and amplitude of observed fluctuations**