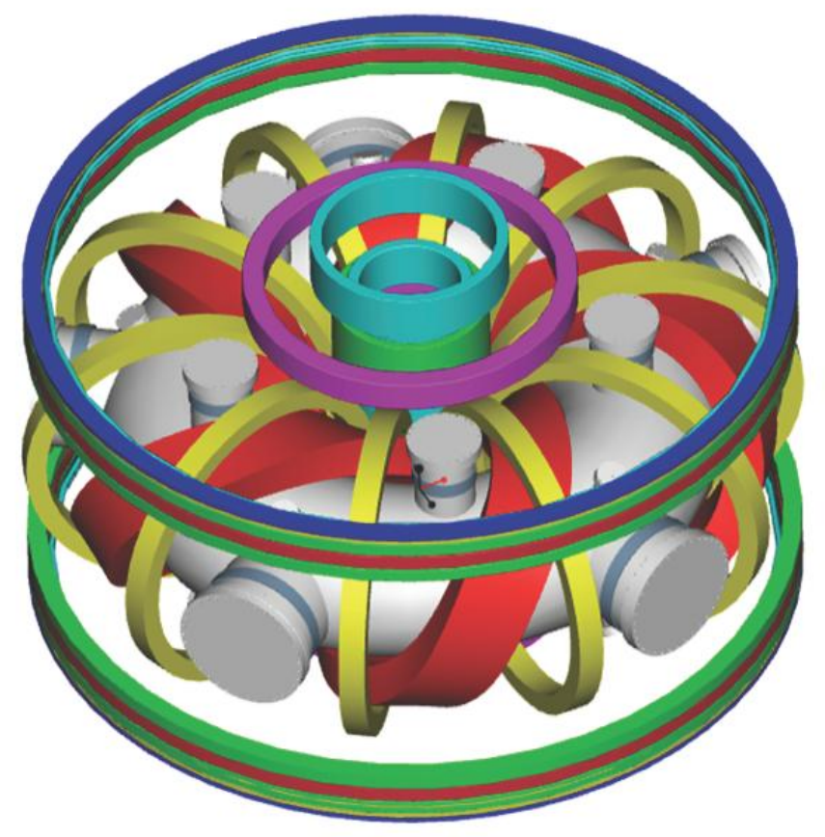
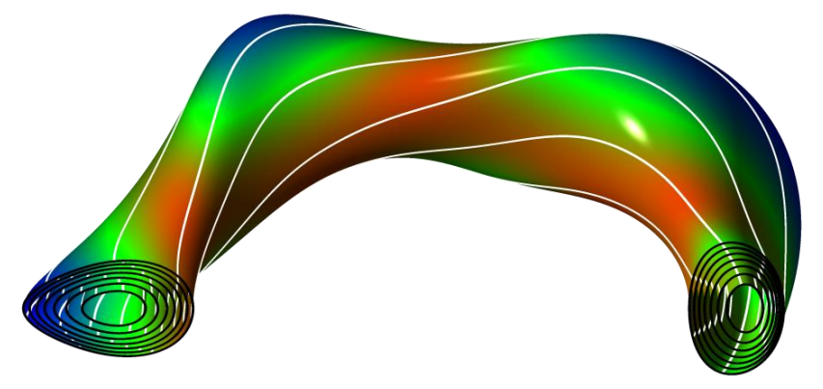
Introduction & Motivation

- Sawteeth oscillations are tied to a 1/1 MHD mode, but other important aspects and not clearly understood.
- How do sawtooth properties depend on total and vacuum transform?
- Due to the unique nature of CTH, the vacuum and total transform can be varied.
- The size of the inversion radius and characteristics such as the rise and crash timescales are investigated as functions of the total and vacuum rotational transform.



Compact Toroidal Hybrid (CTH)



- ***l*** =2, 5 field-period torsatron with auxiliary toroidal field coils
- Operates as conventional torsatron with ECRH plasma generation
- Toroidal plasma current driven with an OH solenoid increases density and temperature

Parameters:

R_0 = 0.75 m P_{input} ≤ 30 kW ECRH a_{vessel} = 0.29 m n_e ≤ 5 x 10^{19} m^{-3} a_{plasma} ≤ 0.2 m
T_e ≤ 200eV B_0 ≤ 0.7 T β ≤ 0.5% I_p ≤ 80 kA Discharge duration – 0.1 s

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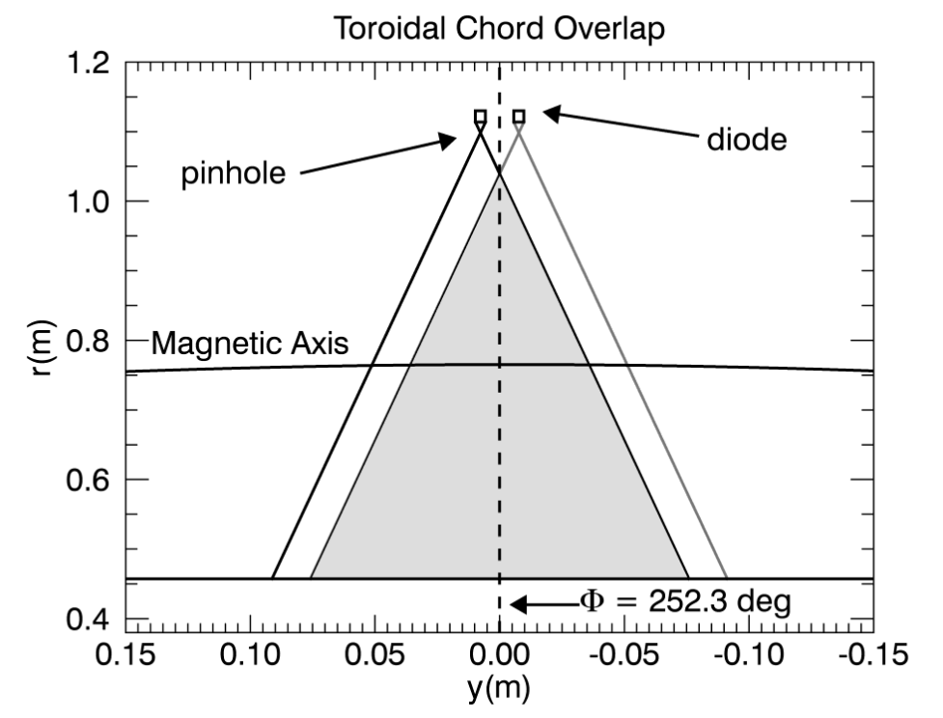
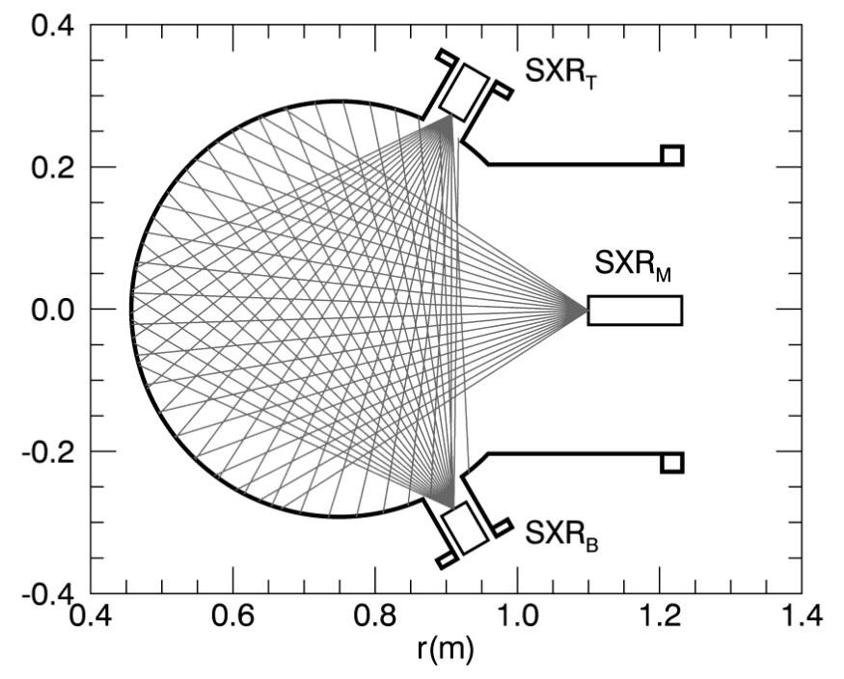
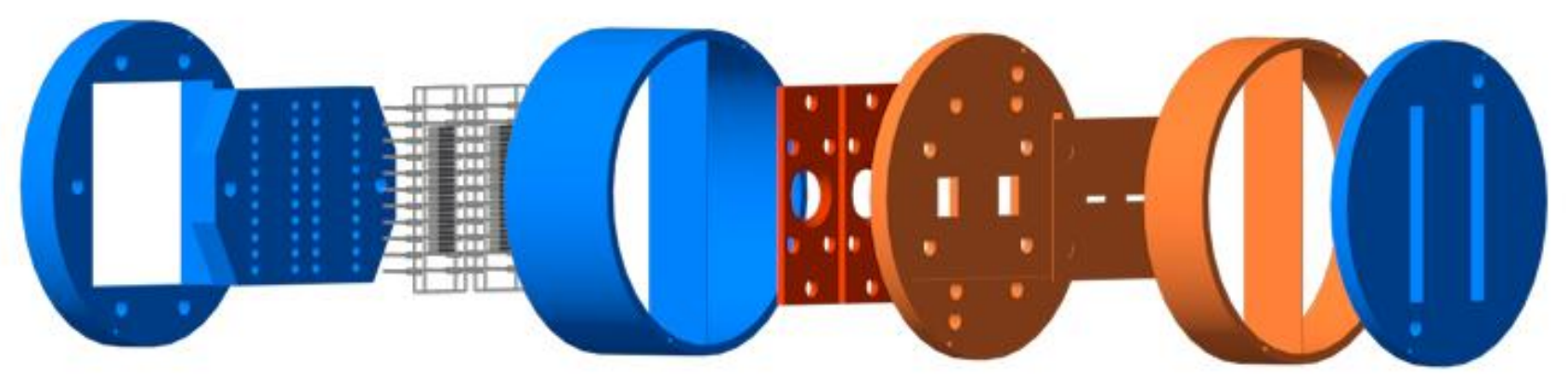
Two-Color Diagnostic on CTH







- 83% of each chord overlaps with the neighboring diode
- 2" in diameter
- Two AXUV20ELG diodes from Opto Diode Inc
- Al (1.0 um, 3.0 um) and C (0.5 um) filters
- Laser cut slits (changeable with vacuum break)
- Toroidal width of slit: 3.175mm
- Poloidal width of slit: 0.25mm

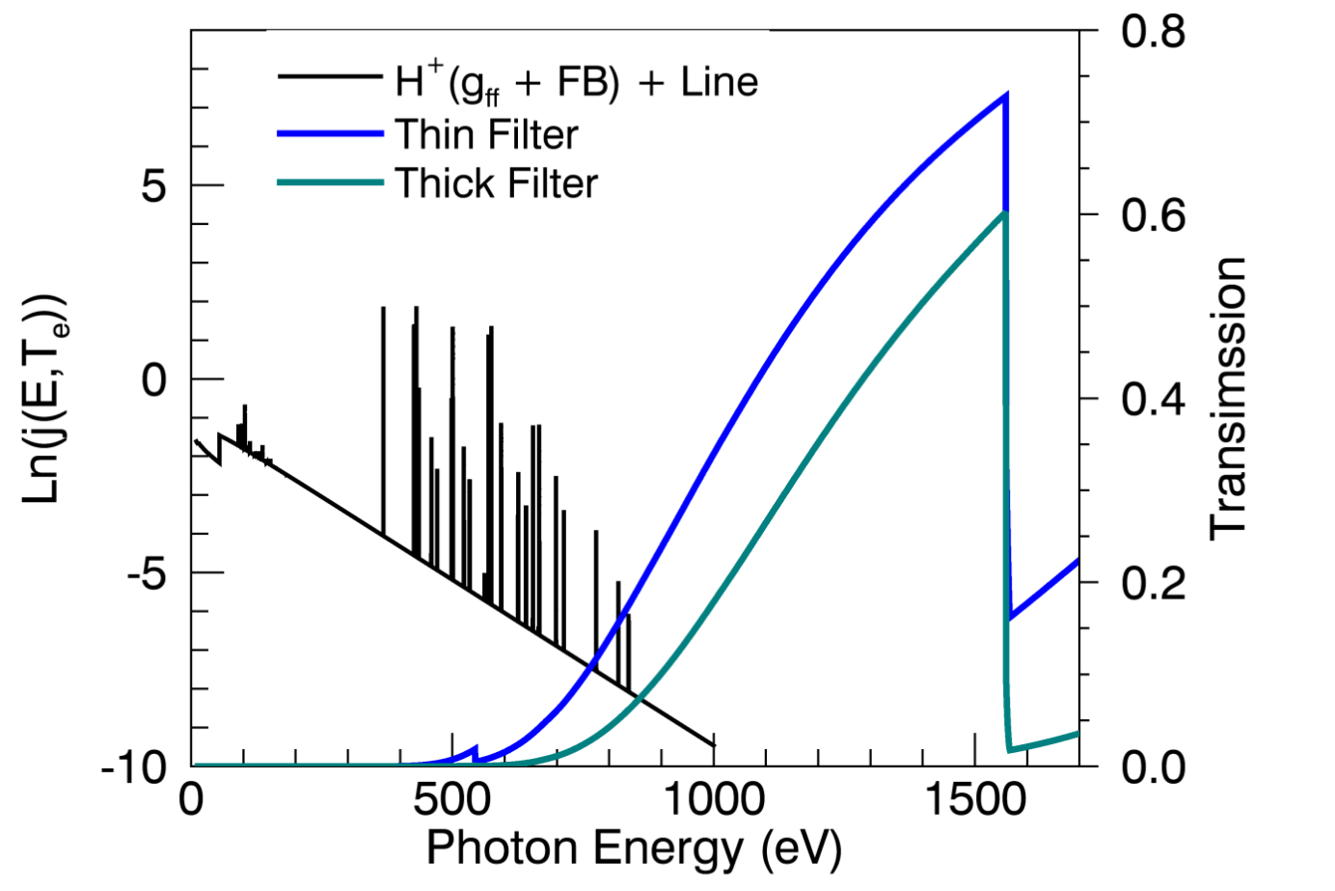
Theory of Two-Color SXR T_e

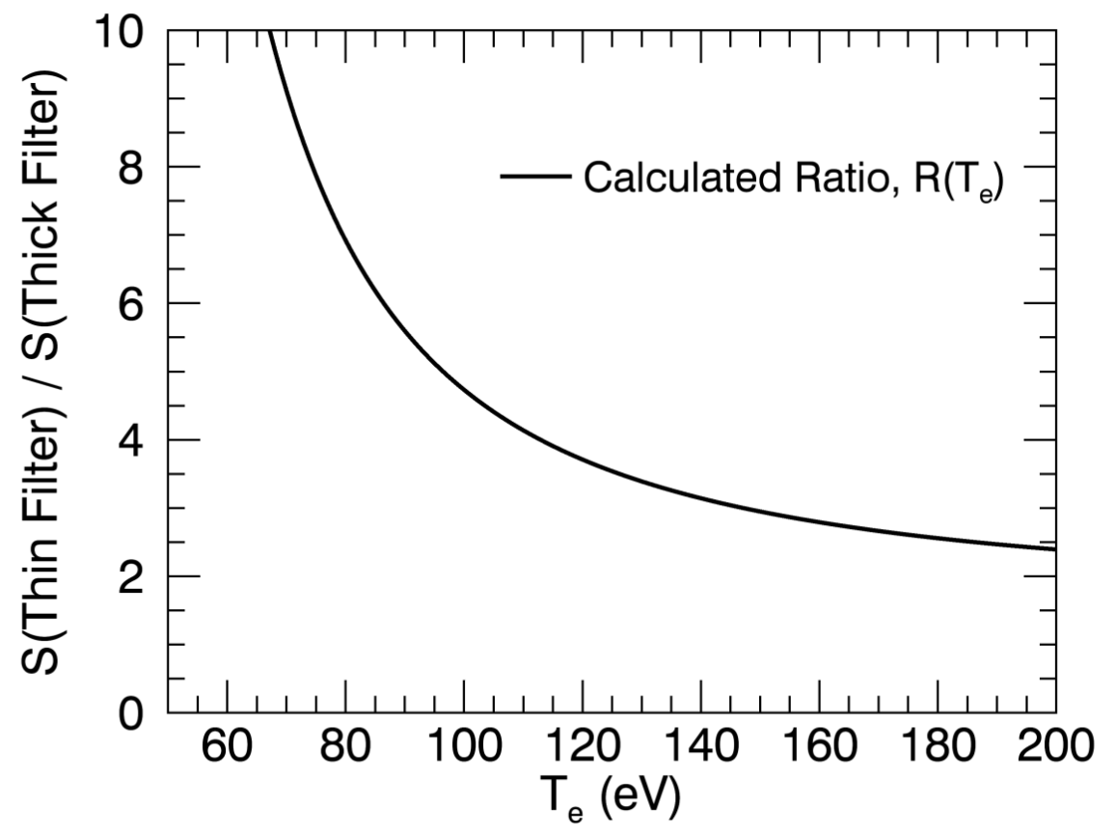
- Each filter has a different photon cut-off energy (**bold lines**) limiting the lower energy range of the bremsstrahlung radiation.
- The filters are 0.5 um C and 1.0um or 3.0 um Al. A 0.5um Al_2O_3 layer was assumed as the dominate impurity for both filters.
- The bremsstrahlung radiation was simulated using Atomic Data and Analysis Structure (ADAS) code[2] at: $n_e = 2*10^{19}$ m^{-3}, T_e = 100 eV.

The SXR signal for each chord with a filter of thickness t_1 is calculated using the formula:

$$SXR(t_1) = k\int_0^{\infty} \mathrm{d}E \int_V j(E,T_e)A(E)T(E,t_1)\frac{\mathrm{d}\Omega}{4\pi}\mathrm{d}r$$

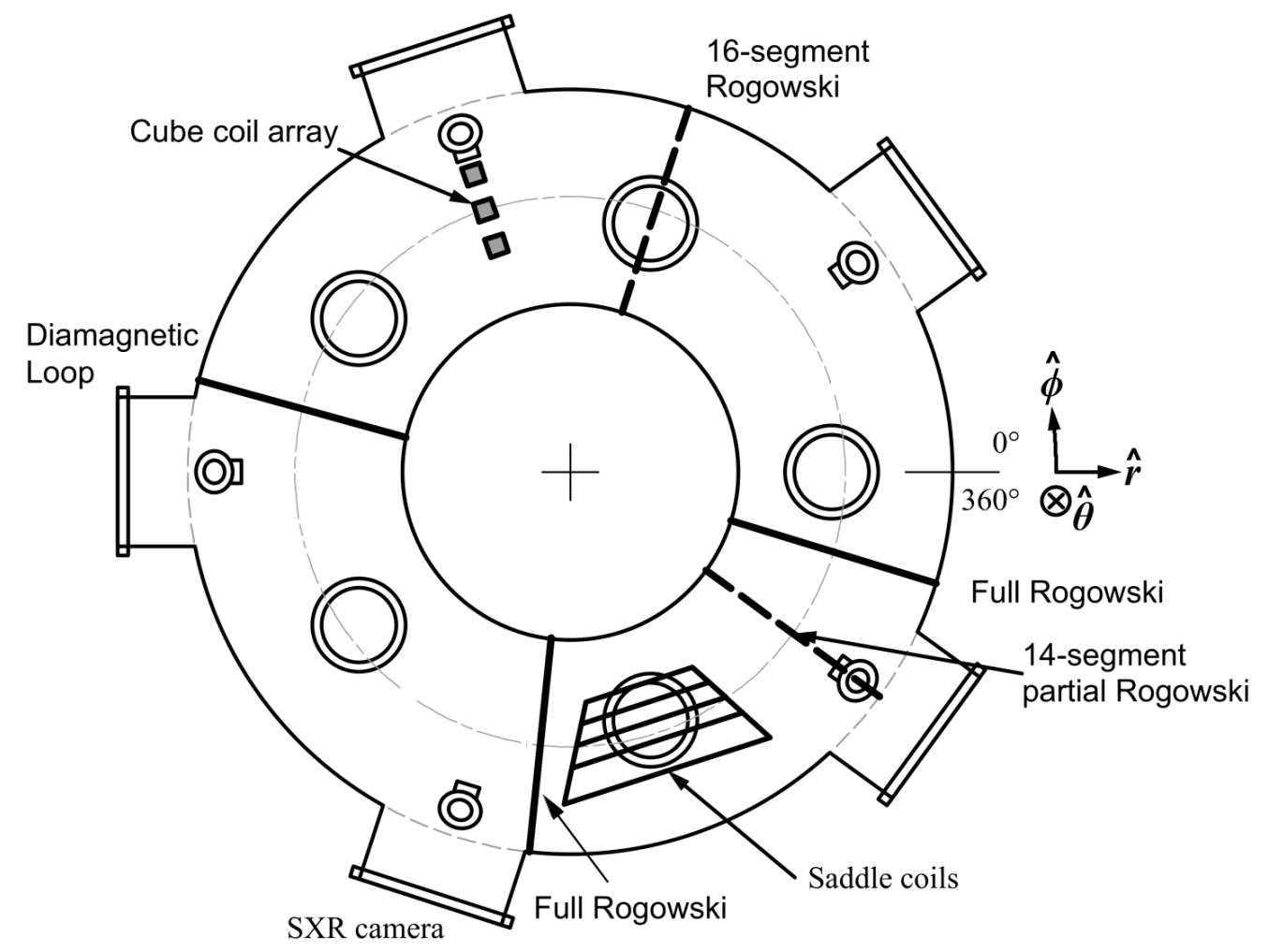
- A(E) is the absorption coefficient of the photodiode, T is the transmission of the filter, j is the bremsstrahlung radiation.
- The temperature is determined by comparing the ratio of experimental signals to the theoretical ratio.



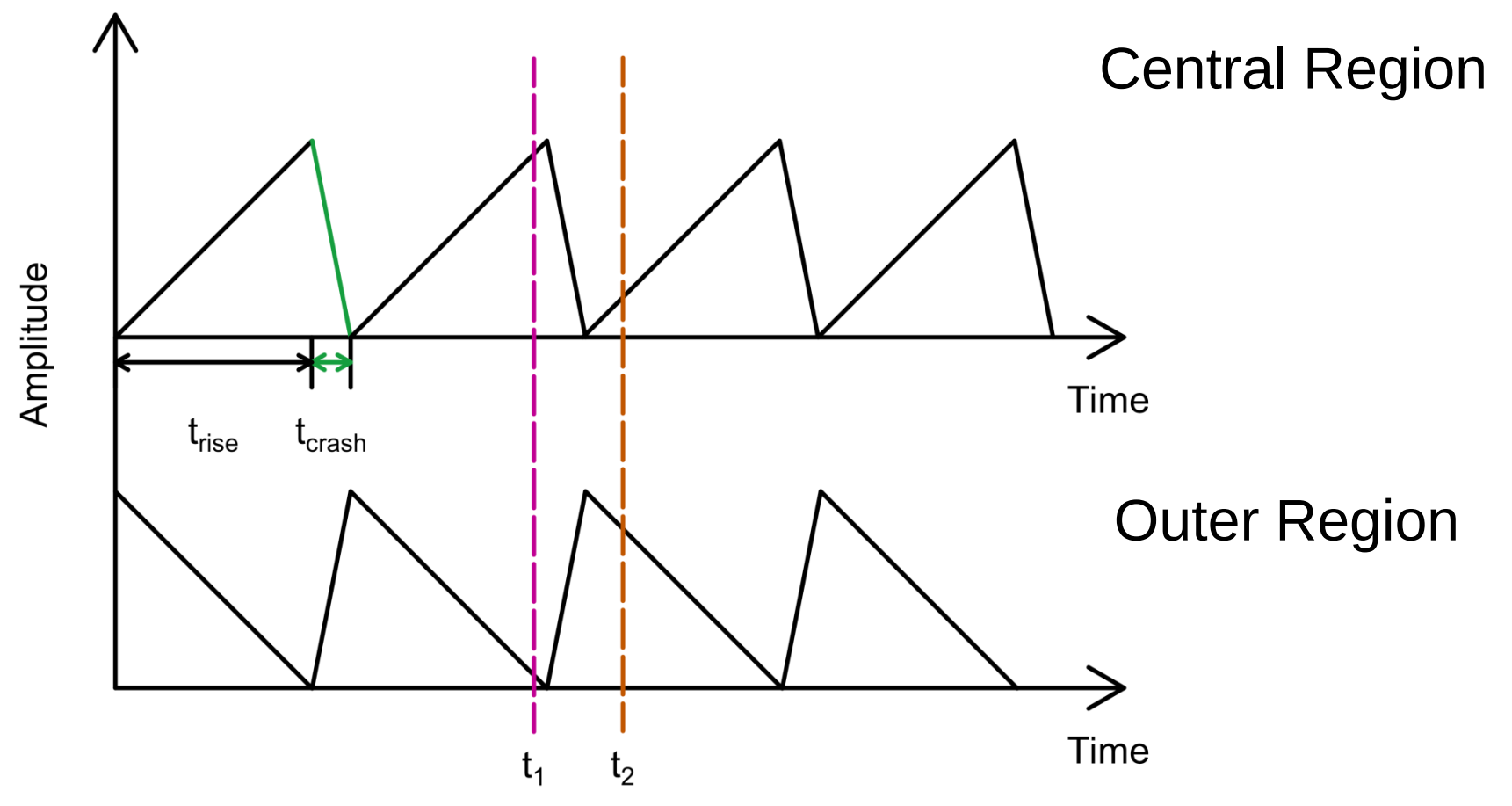


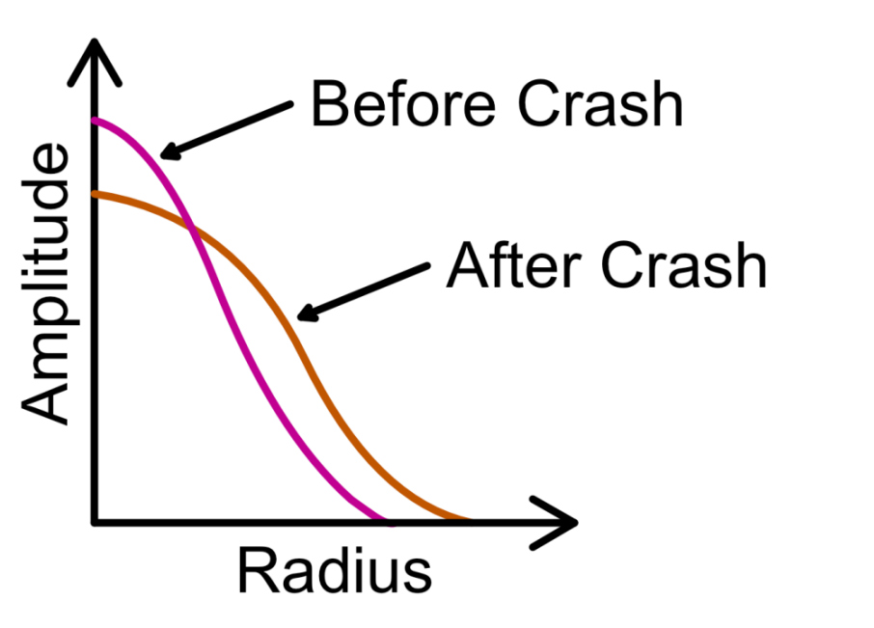
Reconstructions using V3FIT

- V3FIT[3] is used to reconstruct a fully 3D plasma equilibrium.
- V3FIT finds the best fit between data signals calculated from the given equilibrium model and experimental values.
- CTH uses VMEC[4] as the equilibrium solver for V3FIT.
- VMEC is an ideal MHD equilibrium solver. It can calculate the 3D closed nested flux surfaces in toroidal plasmas.
- Experimental values from 186 diagnostics including: Rogowski, cube coils, saddle coils, and SXR signals are used to compute the equilibrium model.



Sawtooth Instability in CTH

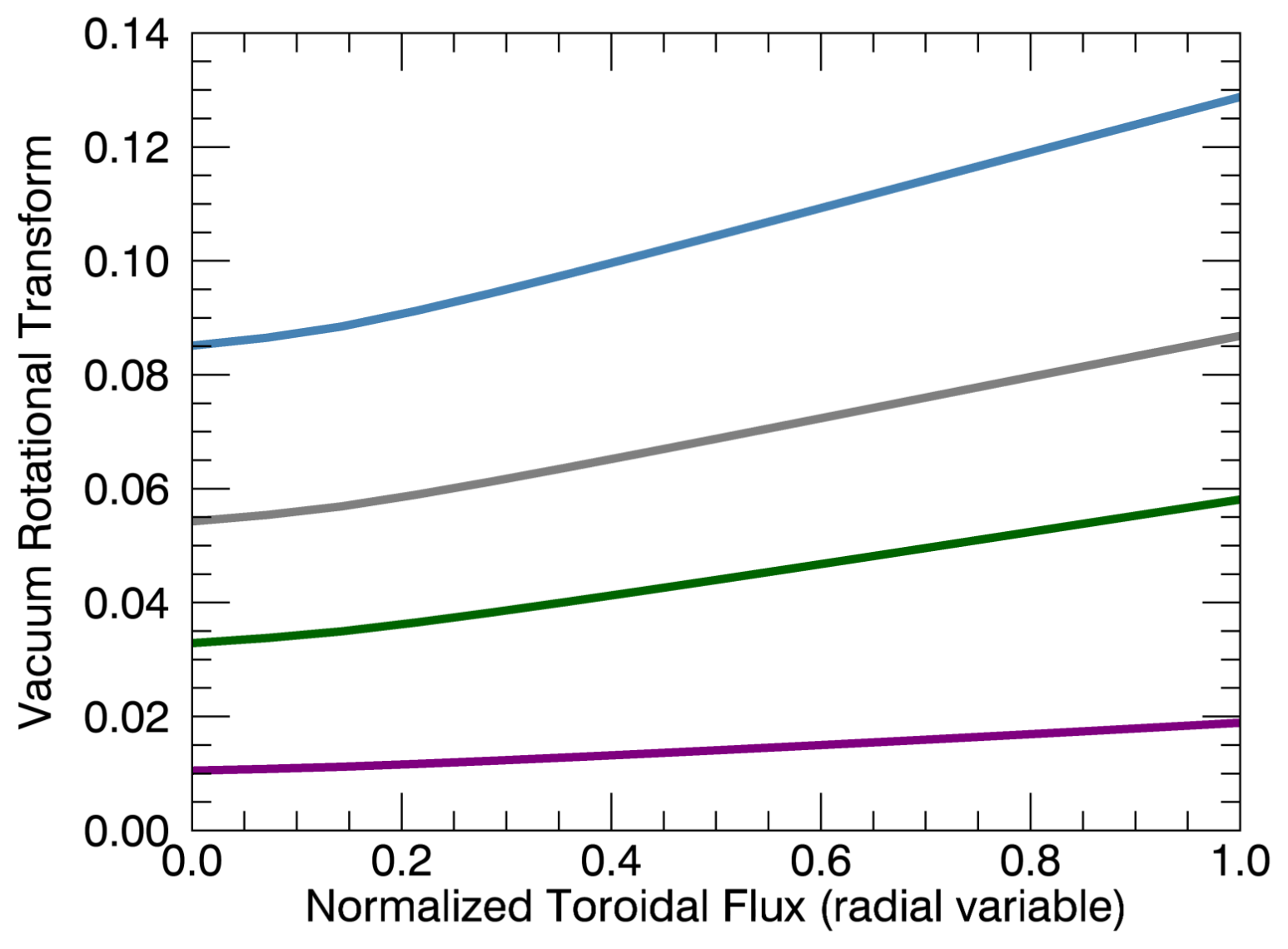


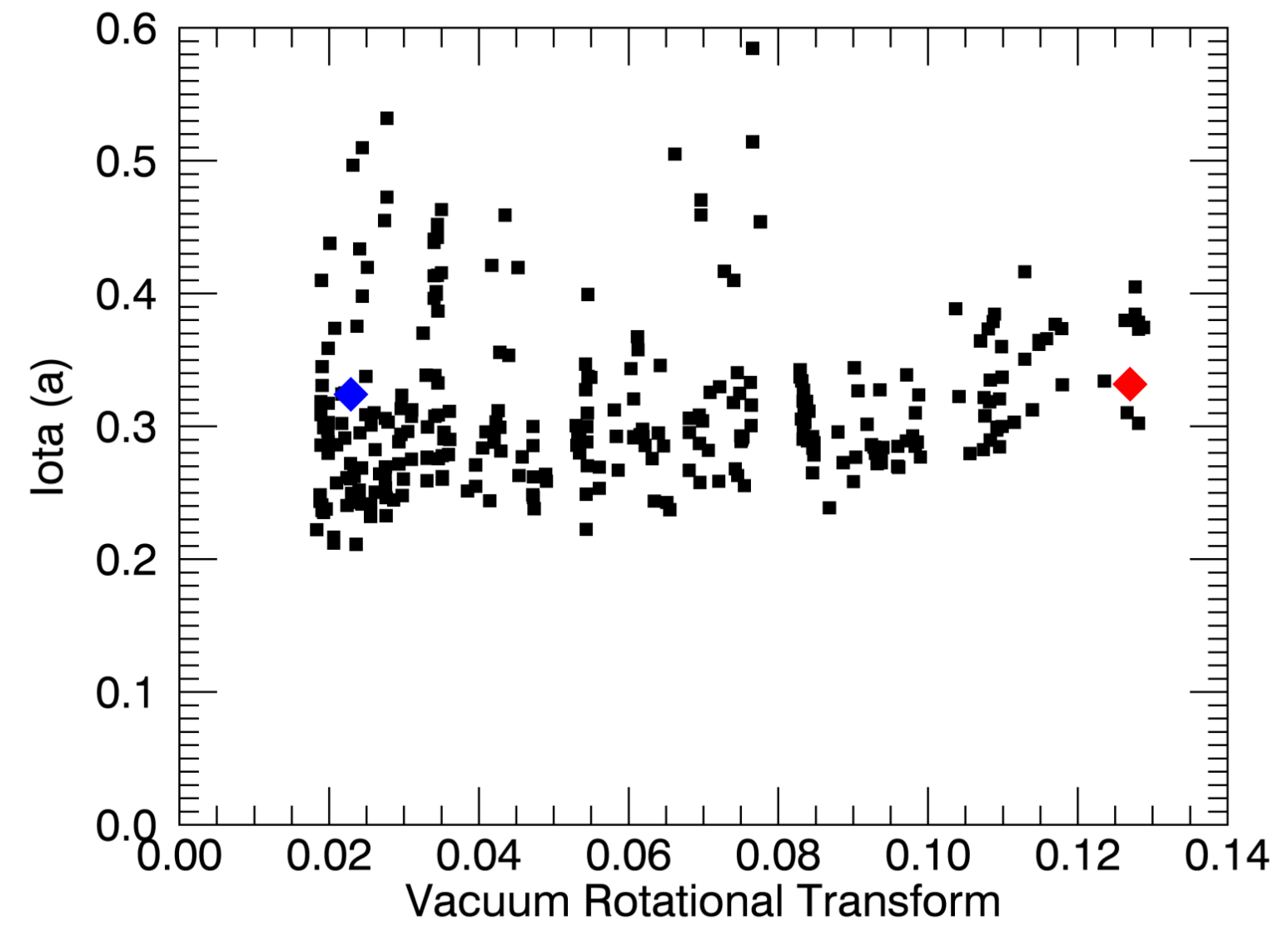


- The core of the plasma is heated ohmically, peaking the plasma current and temperature therefore letting q drop below unity.
- A m = 1, n = 1 MHD mode then grows until the core confinement is lost and expels the energy to the outer regions.

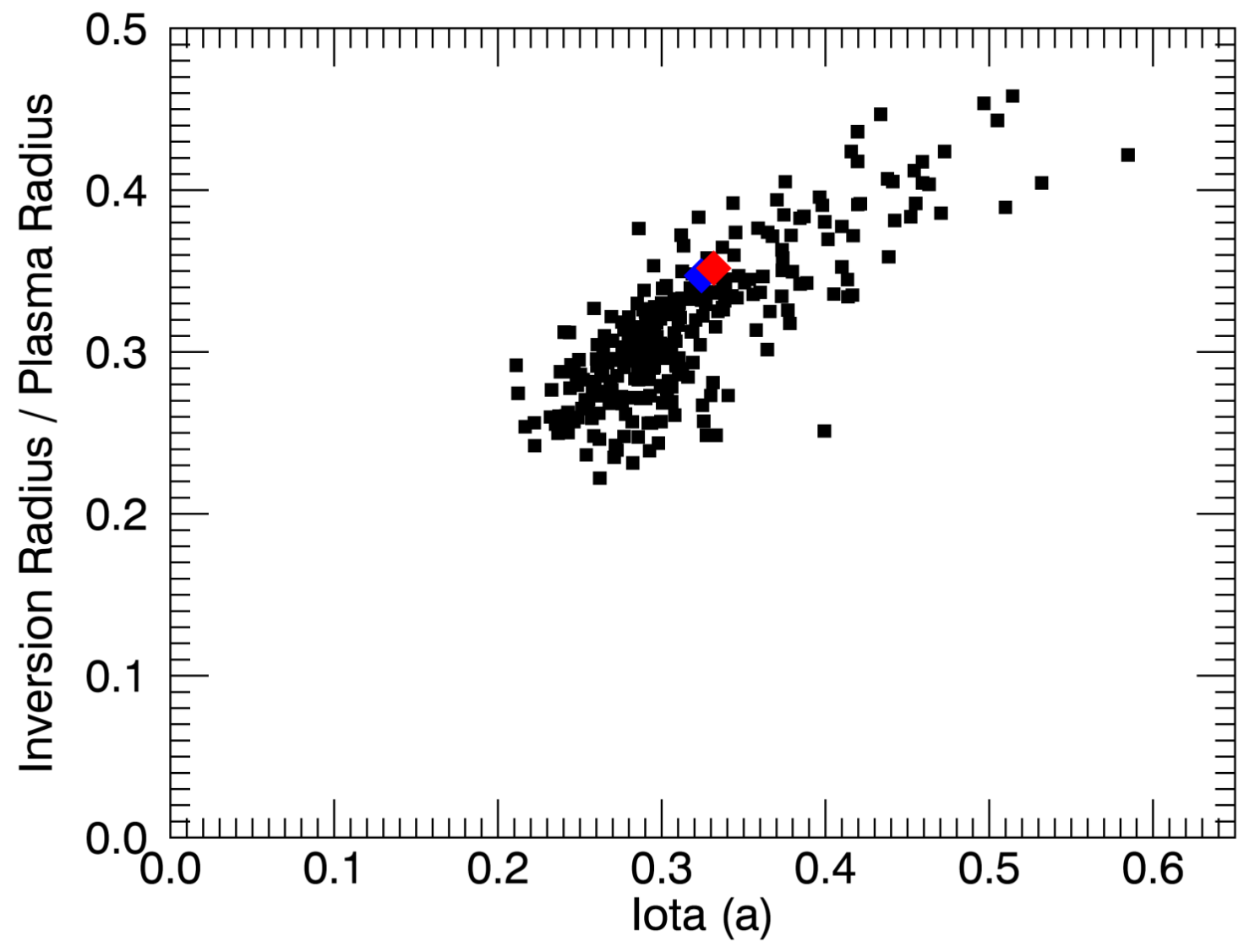
- Schematic of current density and electron temperature profiles
- They peak during the ramp and flatten after a crash.

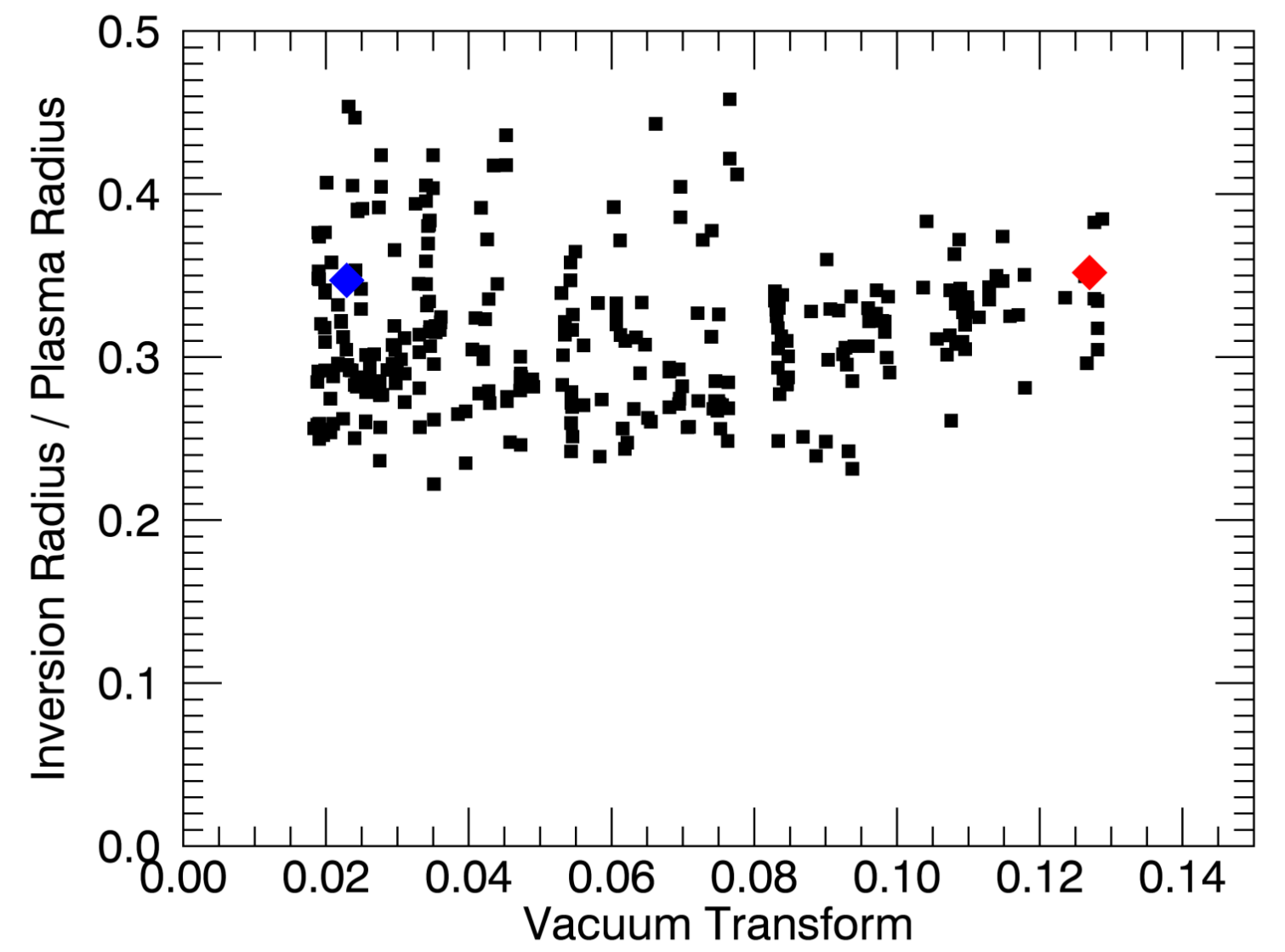
Sawtooth Scan – Changing the vacuum transform





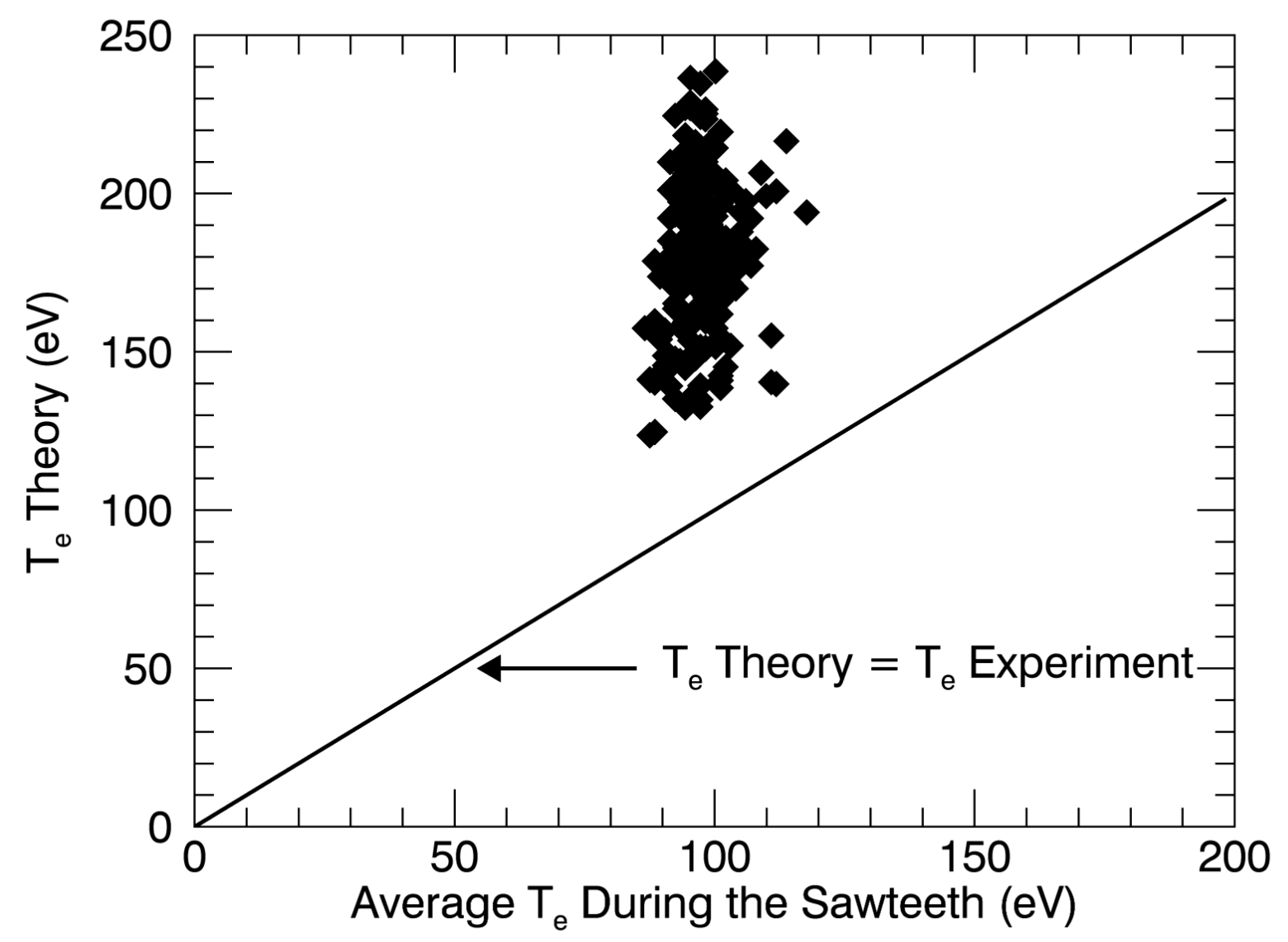
Sawtooth inversion radius scales with total edge transform





- The inversion radius is where the iota surface is equal to 1
- Snider[5] found the ratio of the inversion radius to the plasma radius to increase with increasing iota.
- This phenomena is observed with the sawteeth on CTH.

Temperature for the onset of sawteeth

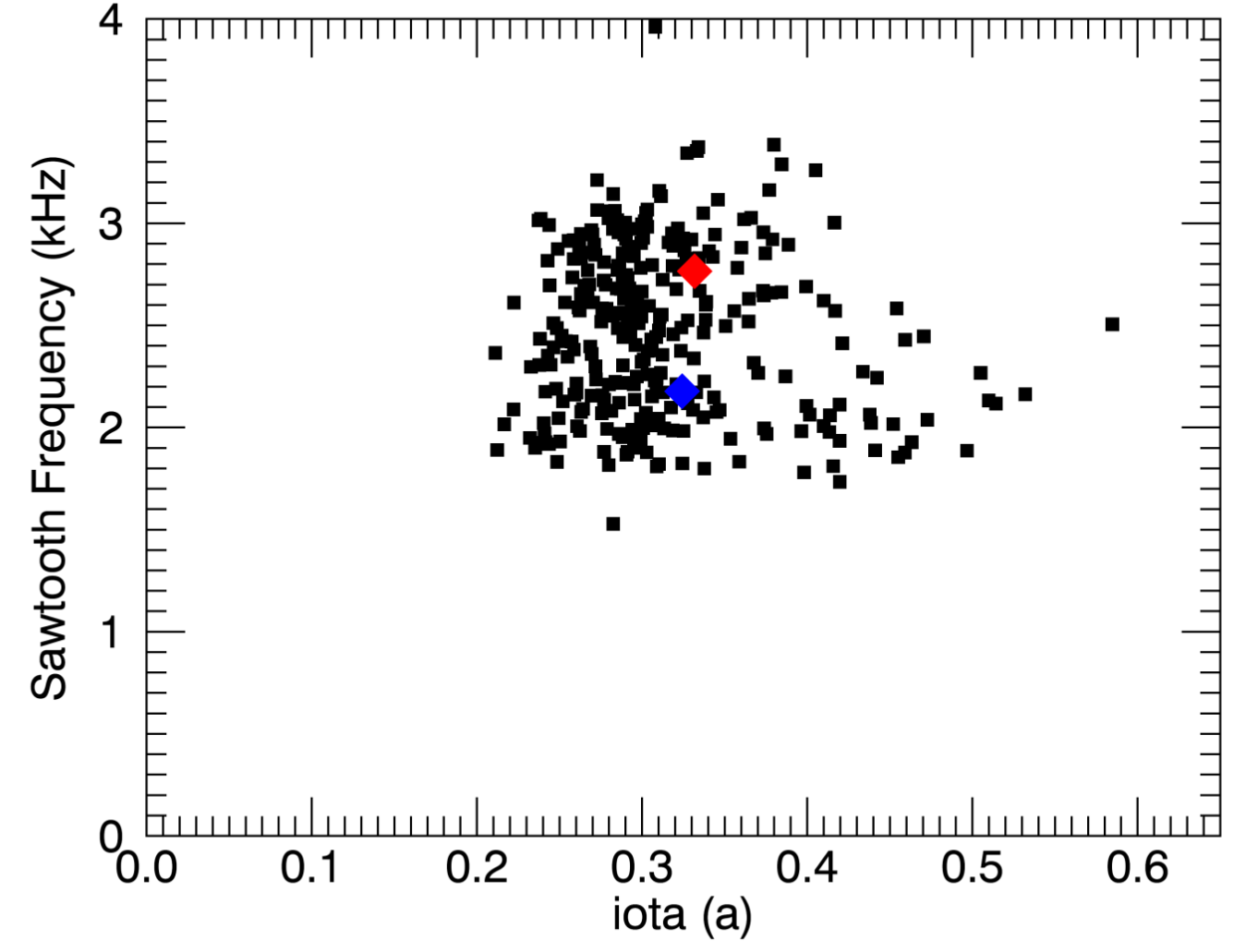


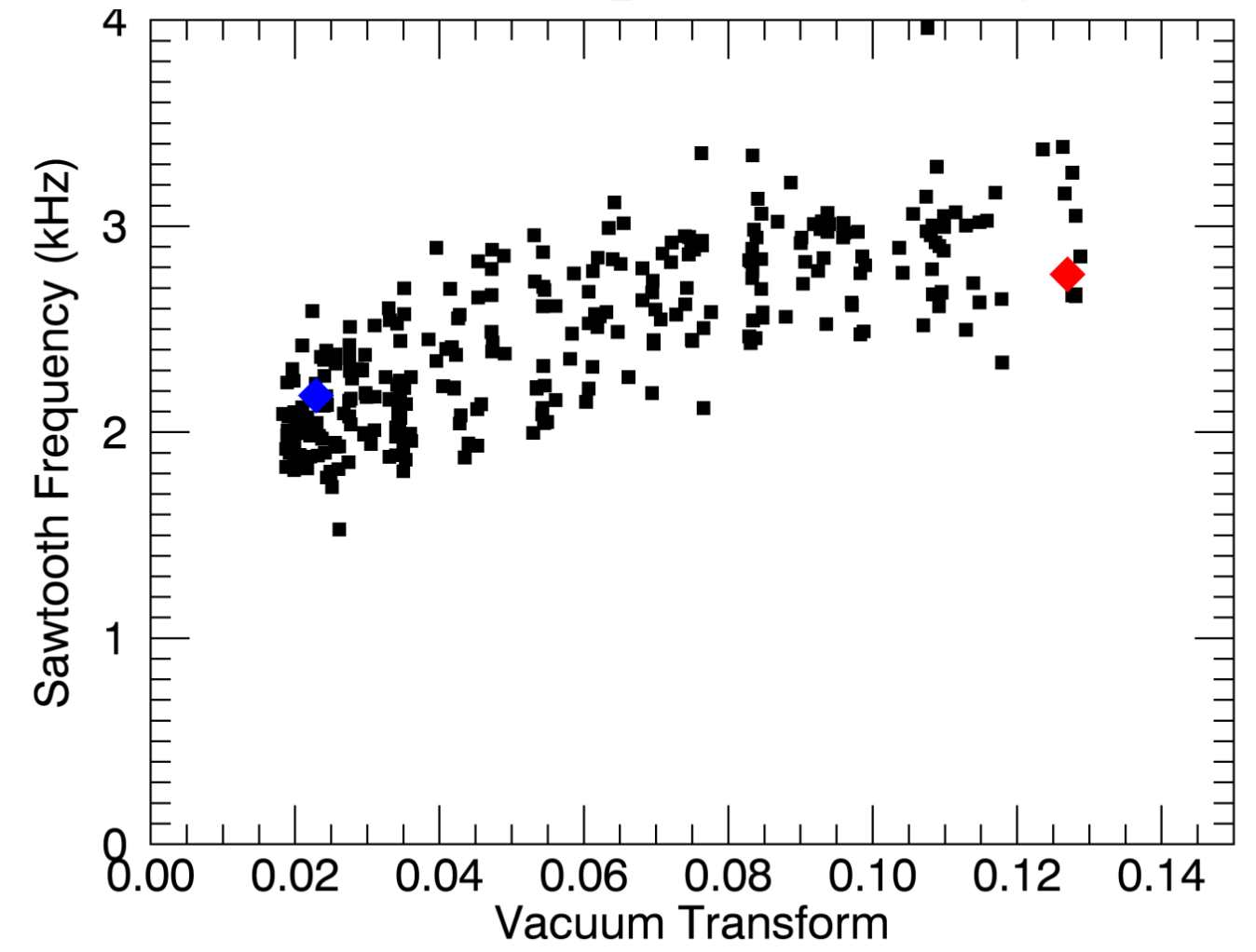
A temperature requirement for the onset of sawteeth with a q = 1 surface in the plasma interior is given by[1]:

$$1 = \frac{4\pi B_z}{\mu_0 V}\eta$$

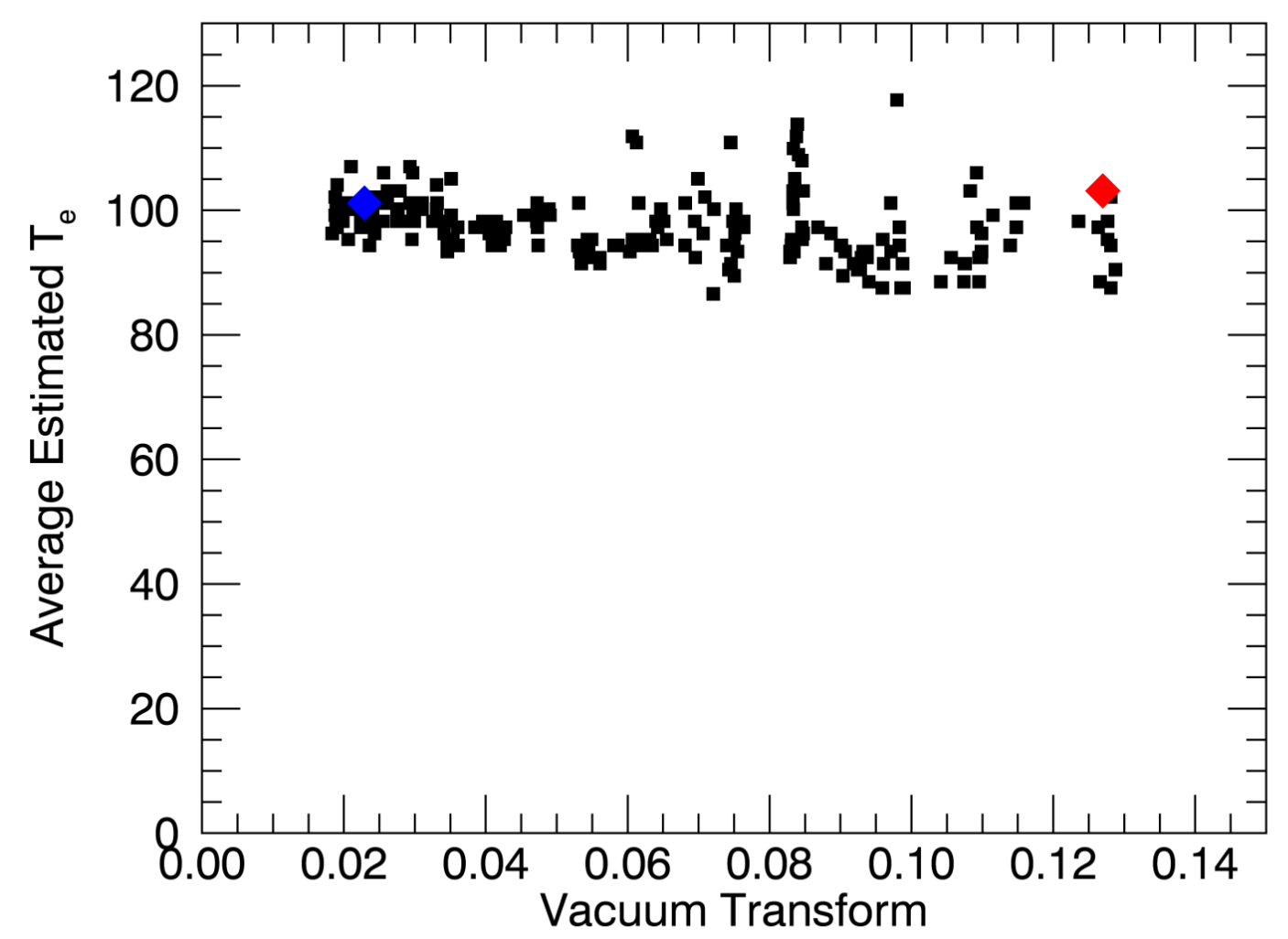
- Using, B_z calculated from reconstructions, ln(Λ) = 15, Z_{eff} = 1.5, and the loop voltage from the experiment gives an estimated temperature using Spitzer resistivity.
- The loop voltage was assumed to be constant across the plasma.
- This x-axis is the average electron temperature in the core of the plasma when sawteeth are observed.

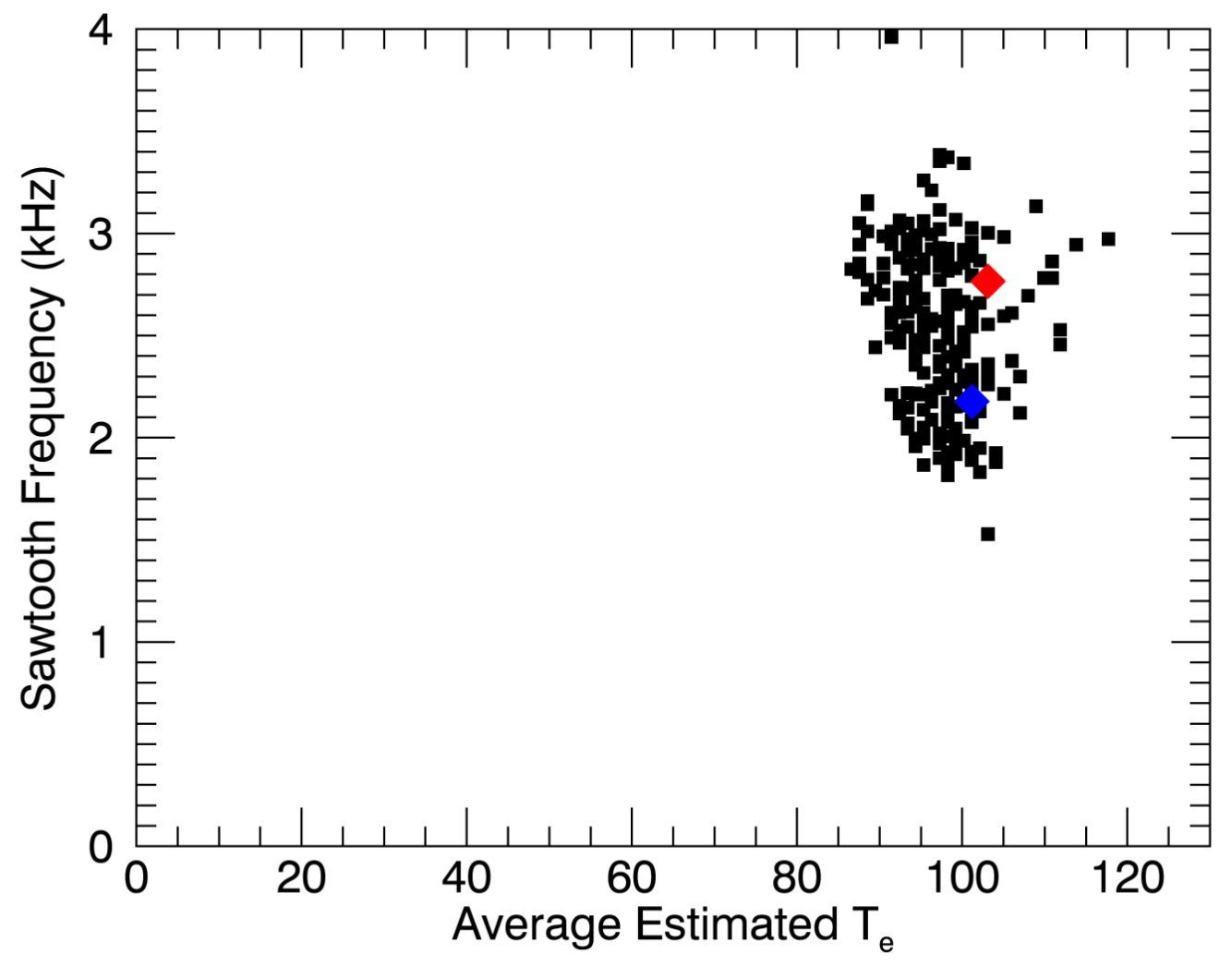
Change in Sawtooth Frequency





- The sawtooting frequency appears to be independent of the total edge transform during a discharge, but dependent on the vacuum transform of the stellarator equilibrium applied before the discharge.
- The sawtooth rise time increases with the vacuum transform, while the crash time does not (not shown).

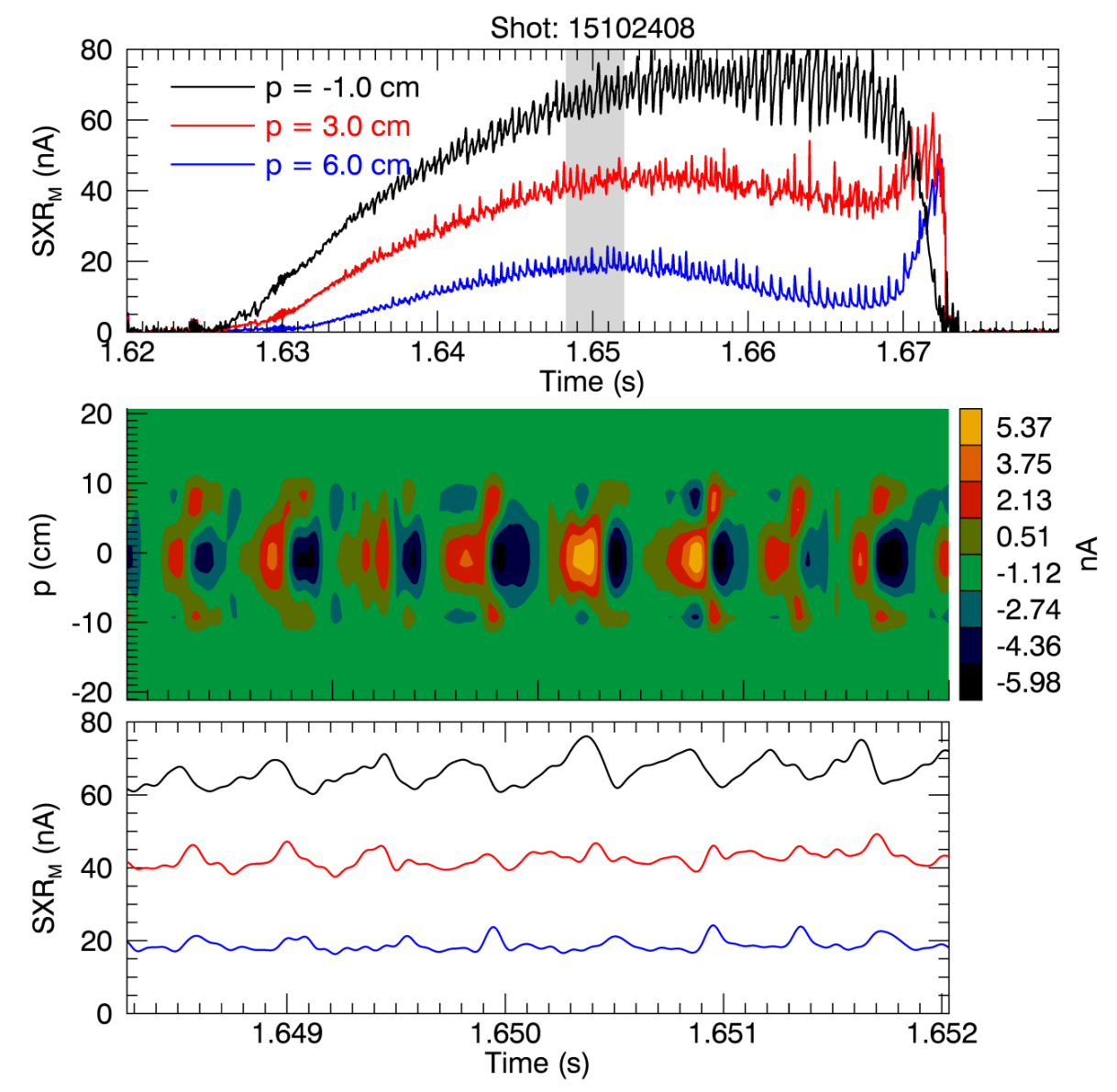




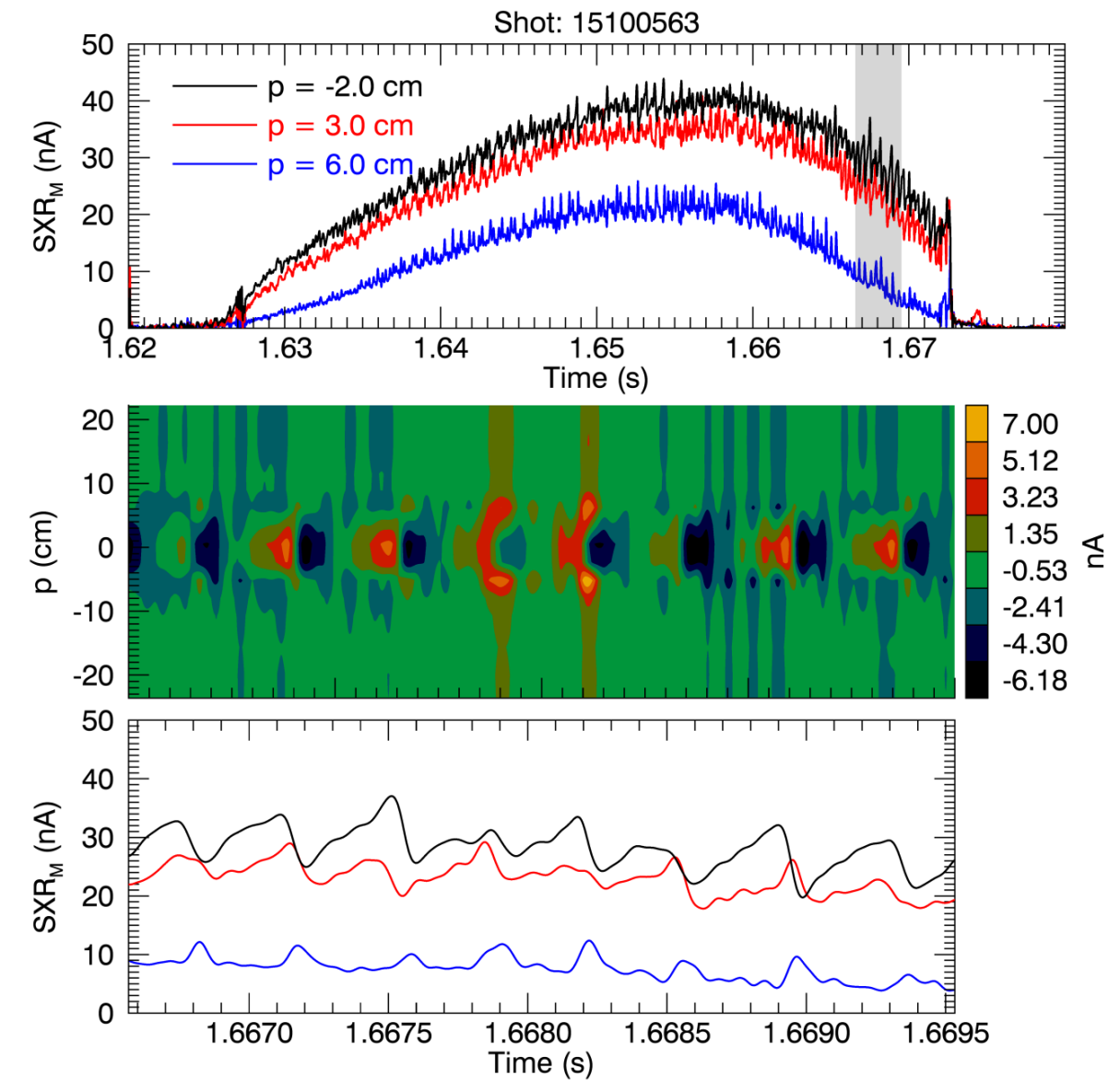
- It has been found that the sawtooth period increases as the central temperature increase on JET.[6]
- The sawteeth period does not seem to scale with electron temperature for CTH plasmas.
- The heating rate a sawtooth was given by Jahns[1], Q_{ei} is the electron-ion energy, Q_R is the radiation loss rate.

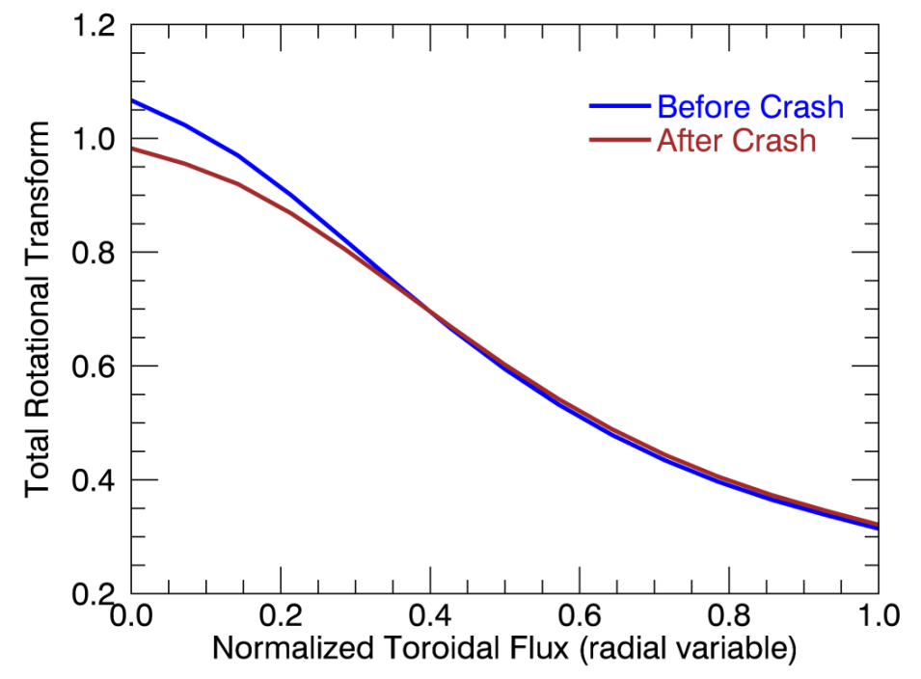
$$\left.\frac{\partial T_e}{\partial t}\right|_{r=0} = \frac{2}{3}\frac{1}{n(0)}\left[\eta J_z^2 - Q_{ei} - Q_R\right]_{r=0}$$

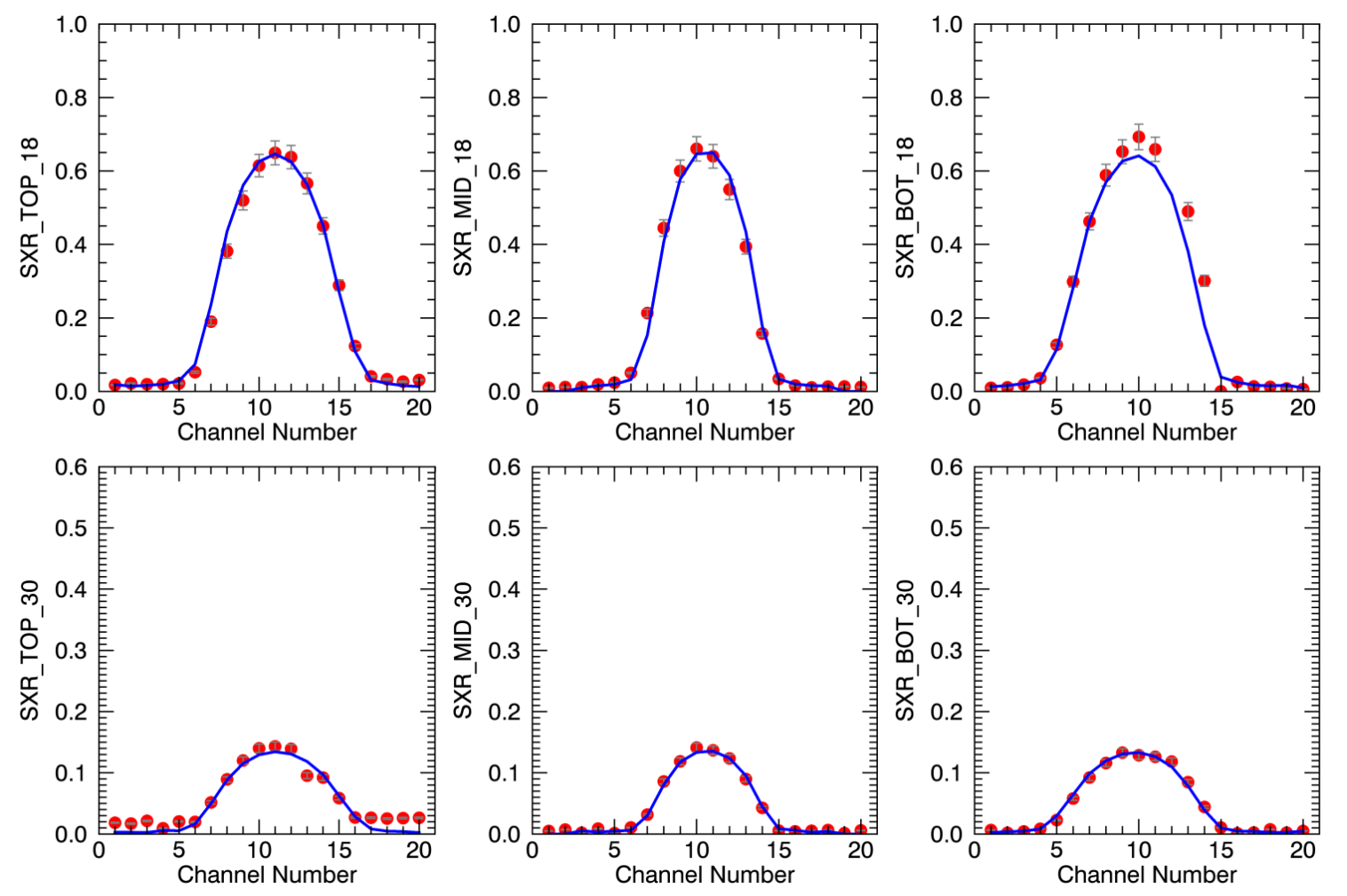
Low vacuum transform

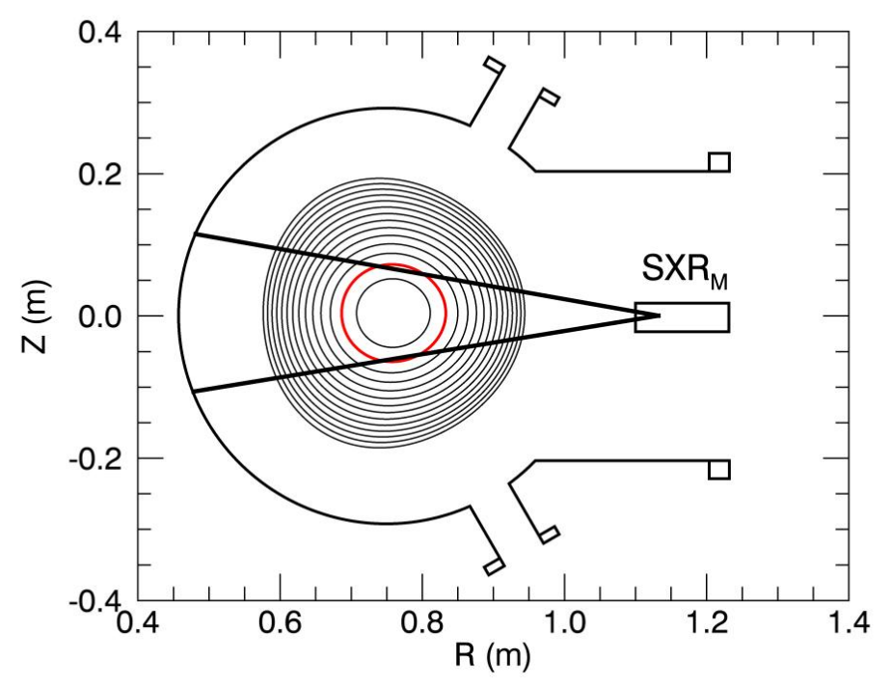


High vacuum transform









- Reconstruction for the low vacuum transform case.
- The reconstructed iota = 1 surface matches up with the measured inversion radius.

References

1. G. Jahns, M. Soler, B. Waddell, J. Callen, and H. Hicks,, Nuclear Fusion, 18, 609 (1978)
2. H. P Summers, The ADAS user manual, version 2.6, 2004, see www.adas.ac.uk
3. J.D. Hanson, S.P. Hirshman, S.F. Knowlton, L.L. Lao, E.A. Lazarus, and J.M. Shields, Nucl. Fusion 49, 075031 (2009)
4. S.P. Hirshman and D.K. Lee, Comput. Phys. Commun. 39, 161 (1986)
5. R.T. Snider, Nuclear Fusion, Vol. 30, No. 11 (1990)
6. P. DeVries, et al. Proc. 28th EPS Conference on Controlled Fusion and Plasma Phy., vol. 25A (2001)