Control of sawtooth oscillation dynamics
using externally applied stellarator transform

D. A. Maurer[1], M. Cianciosa[2], D. A. Ennis[1], J. D. Hanson[1], G. J. Hartwell[1], J. D. Hebert[1], J. L. Herfindal[1], S. F. Knowlton[1], X. Ma[1], M. Pandya[1], N. Roberds[1] and P. Traverso[1]

[1]Department of Physics, Auburn University

[2]Oak Ridge National Laboratory

E-mail contact of main author: maurer@physics.auburn.edu

Abstract. The control of sawtooth oscillations is an active area of tokamak research. Large sawtooth oscillations need to be avoided in ITER, since these large sawteeth couple to neoclassical tearing modes and edge localized modes resulting in serious confinement degradation. Small sawtooth oscillations, however, may be beneficial in preventing impurity and helium ash accumulation in the center of the plasma [1]. Sawtooth oscillations are observed in the Compact Toroidal Hybrid (CTH), a current-carrying stellarator/tokamak hybrid device. CTH has the unique ability to change the relative amount of vacuum transform from stellarator coils to that generated by plasma current to change sawtooth oscillation dynamics. The fractional transform, defined as the ratio of imposed vacuum transform to the total transform was systematically varied from 0.04 to 0.43 to observe changes in CTH sawtooth oscillation behavior. We observe that the normalized inversion surface radius is proportional to the total transform as is found in tokamaks [2]. We also observe that the measured sawtooth period and amplitude decrease with increasing levels of 3D field, as quantified by the amount of vacuum transform imposed. In tokamaks, decrease in the observed sawtooth period has been attributed to a decrease in core electron temperature[3]. The decrease in sawtooth period observed on CTH appears to have no associated decrease in core electron temperature. Finally, the measured crash time of the sawtooth oscillation is independent of the amount of vacuum transform applied, indicating that the final reconnection dynamics of the m = 1 and n = 1 mode are not significantly affected by the 3D stellarator fields.

1. Introduction

The control of sawtooth oscillations is currently an important, active area of tokamak research. Large sawtooth oscillations need to be avoided in ITER, since these large sawteeth couple to neoclassical tearing modes and edge localized modes and possibly induce locked modes also resulting in serious confinement degradation [1]. Small sawtooth oscillations, however, may be beneficial in preventing impurity and helium ash accumulation in the center of the plasma. Sawtooth oscillations are routinely observed in many operational scenarios, see Figure 1 for an example, in the Compact Toroidal Hybrid (CTH), a current-carrying stellarator/tokamak hybrid device. CTH has the unique ability to change the relative amount of vacuum transform from stellarator coils to that generated by plasma current to change sawtooth oscillation dynamics. A method to passively control sawteeth behavior using static three dimensional magnetic fields offers the possiblity to control sawtooth dynamics without the need for active feedback control techniques. Such simple magnetic control actuator realization is very attractive for future reactor designs. These issues are being explored on CTH with it's flexible magnetic configuration. The fractional transform, defined as the ratio of imposed vacuum transform to the total transform was systematically varied from ~ 0.04 to

0.43 (vacuum transform values range from ~ 0.02 to 0.12) to observe changes in CTH sawtooth oscillation behavior.

2. Sawtooth behavior with applied stellarator transform

Sawteeth observed on CTH have similar characteristics as those seem on tokamaks. Figure 1 shows typical sawteeth measured using a 120 channel two color soft x-ray camera system. Three channels are shown in Figure 1(a). A central core channel with impact parameter, p, of 1.2cm, a second with p=8.2cm and a third with p=14cm relative to the midplane of the device are shown. Strong sawtoothing is observed close to the magnetic axis while for the largest impact parameter we observe inverted sawteeth. A bi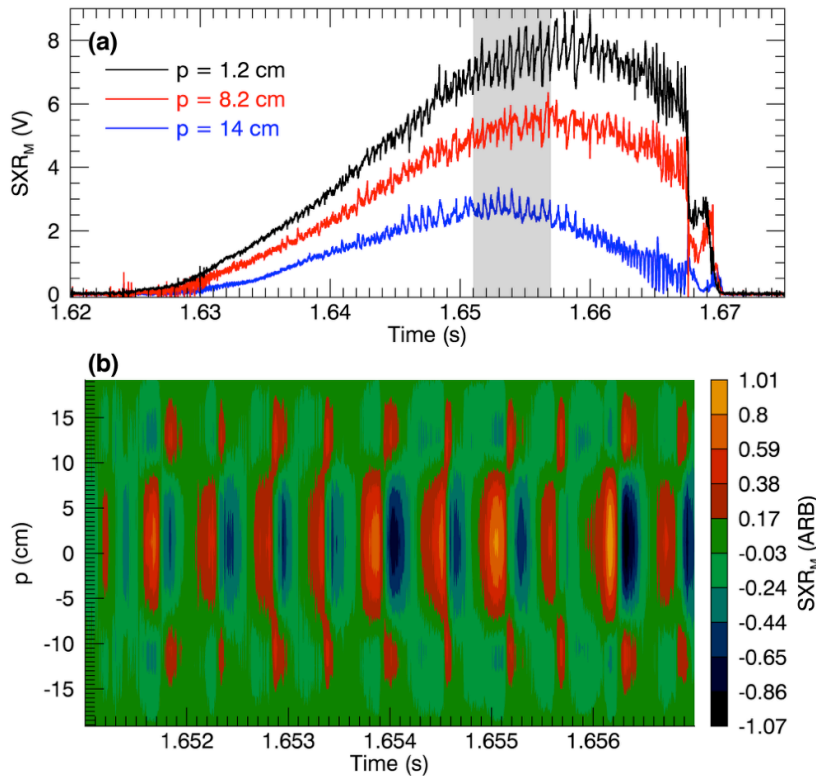orthogonal decomposition analysis technique is used to extract the position of the inversion surface and structure of the n=1, m=1 mode from x-ray signals. In Figure 1(b) a contour plot of one of the 20 channel arrays is presented, that has been filtered to clearly show the emissivity inversion radius. We observe that the normalized inversion surface radius is proportional to the total transform from both the plasma current and external vacuum transform as is found in tokamaks, where it is derived only from plasma current [2]. Measurements were made over an ensemble of plasmas that were sawtoothing and the vacuum transform level was systematically varied to observe any change in sawtooth dynamical

Figure 1. *Soft x-ray measured chordal brightness as a function of time for three channels that span the core and edge plasma are shown in (a), and a contour plot of the rise and crash of several sawteeth for a 20 channel detector array shown in (b).*

behavior. The amount of vacuum transform is used as a measure or proxy for the amount of 3D magnetic shaping being applied to the equilibrium. Figure 2 shows the effects of varying the vacuum transform on sawtooth temporal characteristics. In Figure 2(a) we plot the observed sawtooth frequency for the ensemble of discharges studied. A clear trend is seen that the observed frequency of the sawteeth increases (decreasing sawtooth period) with the addition of external vacuum transform. Whether this observed increase is due to changes in core heating and equilibrium changes is under study. Another possibility is that the n=1, m=1 mode stability could be affected and leads to mode onset earlier in the sawtooth cycle, thus initating a crash earlier in time and hence a reduced sawtooth period.

In addition, as shown in figure 2(b) we also observe that the sawtooth crash time is not systematically affected by the level of applied vacuum transform. This behavior indicates that
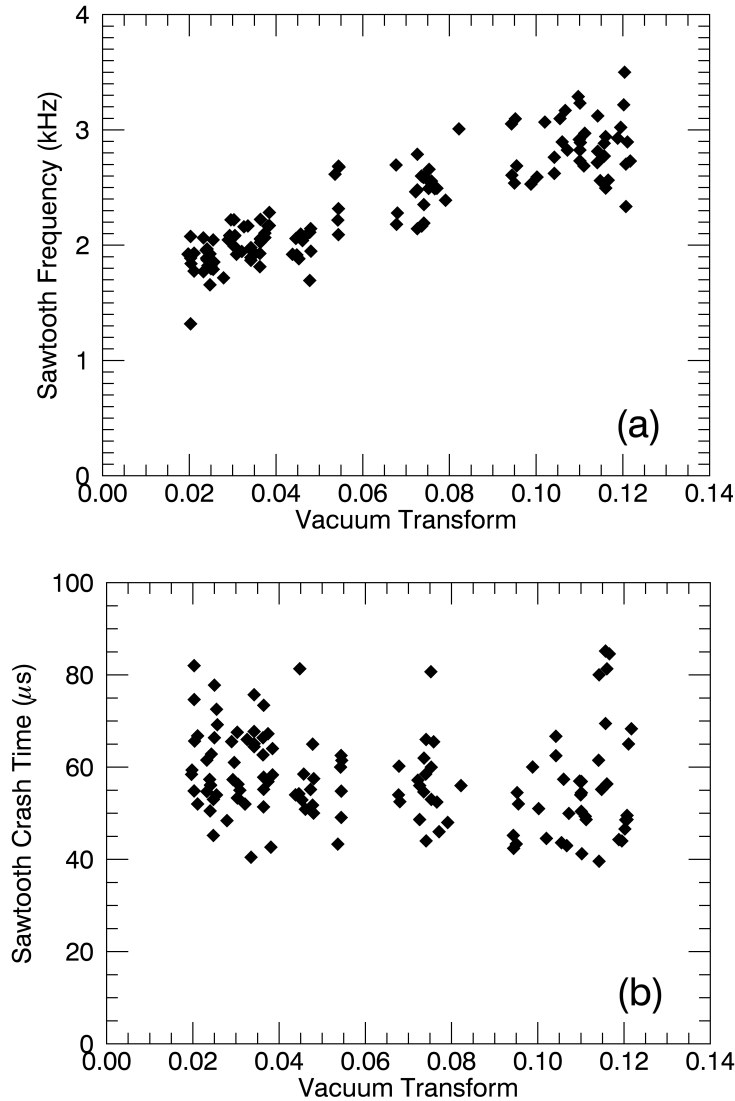
the final nonlinear dynamics of the n=1, m=1 mode enveloping the core plasma is not significantly changed by the 3D fields that are applied. In tokamaks, decrease in the observed sawtooth period has been attributed to a decrease in core electron temperature [3]. The decrease in sawtooth period observed on CTH appears to have no associated decrease in core electron temperature decrease as measured by the two color camera system. However, there are uncertainties in the interpretation of the two color measurement that preclude a definitive statement at this time as to the behaviour of the core electron temperature. Also observed during these experiments is a systematic change in the amplitude of the sawteeth. This effect is shown in Figure 3, where the amplitude of the sawtooth crash versus the normalised inversion surface radius is plotted. The crash amplitudes are color coded as to their respective value of the vacuum transform, or amount of 3D shaping. For similar inversion surface radius, the amplitude of a crash is smaller for higher levels of transform as measured by the integrated brightness.

Figure 2. Sawtooth frequency versus the amount of 3D shaping applied, as quantified by the value of the discharge vacuum transform, showing increased sawtooth cycle frequency in (a). The sawtooth crash time does not show a distinct correlation with the amount of 3D shaping as shown in (b) indicating that the crash reconnection physics is not significantly effected.
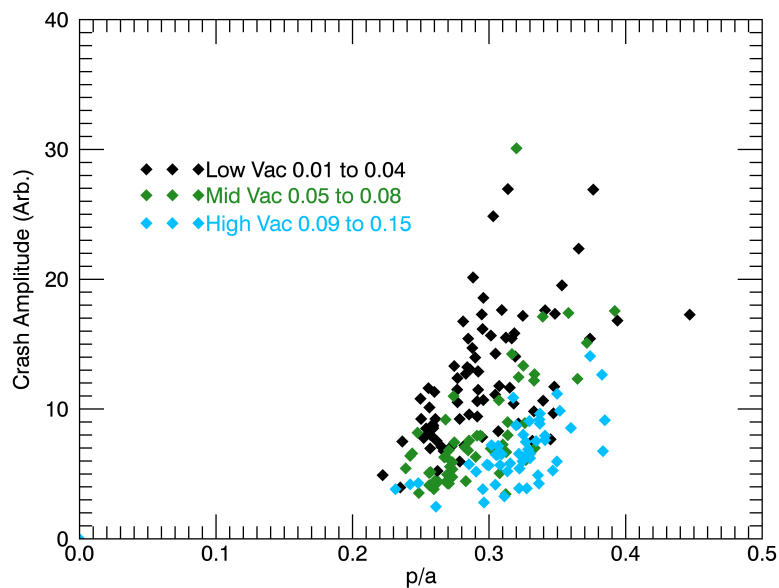
Nimrod modeling of the sawtooth dynamics is currently underway and will help to shed light on the underlying physical mechanisms on the behavior of the observed sawteeth in CTH.

at work in these experiments with 3D magnetic fields sawteeth in CTH.

In summary, we have experimentally shown that the use of strong 3D magnetic surface shaping can be used to passively control the frequency of sawteeth as well as their amplitude. This technique thus offers an additional method for control of large sawteeth that can lead to deleterious effects for tokamak discharges by coupling to other forms of MHD including neoclassical tearing modes and locked modes leading to plasma disruption and loss of confinement.

Figure 3. Sawtooth crash apmlitude versus the normalised inversion surface radius. The crash amplitudes are color coded as to their respective value of the vacuum transform, or amount of 3D shaping. For similar inversion suface radius, the amplitude of a crash is smaller for higher levels of transform as measured by the integrated brightness.

[1]   T.C. HENDER, et. al., Nucl. Fusion, 47, S128, (2007).

[2]   R.T. SNIDER, Nuclear Fusion, Vol. 30, No. 11 (1990)

[3]   P. DeVRIES, et al. Proc. 28th EPS Conf. on Controlled Fusion and Plasma Phy., vol. 25A (2001).