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COMPACT IGNITION TOKAMAK

By

G. Bateman

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Delaying Sawtooth Oscillations in the Compact Ignition Tokamak

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A combination of pellets, off-axis heating, and current ramp is used to delay the onset of sawtooth oscillations for 3.4 seconds and achieve ignition with less than 0.2-second confinement time in a 1-1/2-D BALDUR simulation of the Compact Ignition Tokamak. Deuterium and tritium pellets are injected into an initially cold, relatively low density plasma, where they cool the center and produce a very centrally peaked density profile. A centrally peaked density profile ($n_{e0}/\langle n_e \rangle = 4.0$) is subsequently maintained by an inward particle pinch. Twenty megawatts of auxiliary heating is applied halfway between the magnetic axis and the edge of the plasma for 2 seconds after the pellets are injected. The plasma ignites and then burns from the time the auxiliary heating is turned off until the first large sawtooth crash occurs at 3.4 seconds. The burn would be expected to continue after that only if the sawtooth period is sufficiently long (roughly 0.3 seconds or longer).

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Introduction

Sawtooth oscillations are observed to play a dominant role in transport simulations of the Compact Ignition Tokamak.¹⁻³ At the full design current of 10.0 MA, the sawtooth mixing radius is typically 73% of the plasma half-width in the CIT-1 design. Sawtooth mixing results in broad density and temperature profiles that are not conducive to ignition in plasmas with low energy confinement times. In an effort to improve the likelihood of igniting the Compact Ignition Tokamak with L-mode confinement, various methods are explored to delay the onset of sawtooth oscillations and to maintain a centrally peaked density profile for as long as possible.

Section 1 describes the simulation model and geometry used. Section 2 describes the most successful combination (found to date) of pellet injection, off-axis heating, and current ramp, which delayed sawtooth oscillations for the longest time and lead to ignition with the lowest energy confinement time.

1. Simulation Model

The 1-1/2-D BALDUR transport code at Princeton^{4,5} is used to simulate the Compact Ignition Tokamak CIT-1 design. The plasma parameters used for this design are given in Table I. These plasma parameters represent maximum values that are achieved after the start-up of the plasma. Note that, in the simulation, it is easier to specify and hold fixed the volume-averaged density, which is proportional to the total number of particles, rather than the line average density. During large sawtooth oscillations, the line average density can bounce up and down while the volume-averaged density remains constant.

A typical contour plot of the flux coordinates computed within the code is shown in Fig. 1. Note that the inner flux surfaces are usually less elongated than the outer surfaces (typically $b/a \approx 1.6$ near the magnetic axis and $b/a = 1.8$ as prescribed for the outer flux surface) and most of the Shafranov shift occurs in the outer flux surfaces. After each sawtooth crash, when the pressure profile within the mixing radius is flat, that entire central part of the plasma is paramagnetic with respect to the toroidal

Table 1: Plasma parameters used in simulations of the Compact Ignition Tokamak.

Major Radius	1.225	m
Half-width	0.453	m
Elongation	1.8	
Triangularity	0.2	
Volume	8.73	m ³
Cross-sectional Area	1.15	m ²
Vacuum Toroidal Field	10.47	tesla
(measured at $R =$	1.225	m)
Max. Plasma Current	10.0	MA
$\langle n_e \rangle$	5.0×10^{20}	m ⁻³

magnetic field, even if the total beta is high under these conditions; all the diamagnetic effects are concentrated in the region outside the mixing radius. The equilibria were computed with a version of Hirshman's equilibrium moments code⁶⁻⁸ in which the flux surfaces are spaced at intervals of equal toroidal flux.

The transport model used in these simulations is based on a model developed by Singer and Ku^{9,10}:

$$\chi_e = \frac{\text{const.}}{R^2 n_e^{7/8}} r \left(\frac{T_e q^{0.8}}{r^{0.4} B^{0.6}} \right)^2 \left(\frac{r}{p} \frac{dp}{dr} \right) \quad (1)$$

$$\chi_i = 0.2\chi_e + \chi_i^{nco} \quad (2)$$

$$D = 100 \quad \text{cm}^2/\text{sec} \quad (3)$$

$$v = 12.68r/a \quad \text{cm/sec.} \quad (4)$$

On each flux surface, χ_e is the flux-surface-averaged electron thermal diffusivity [meter²/second], r is the flux-surface half-width in meters, R is the major radius to the flux-surface midpoint in meters, n_e is the electron number density in particles per cubic meter, T_e is the electron temperature

in keV, q is the magnetic q -value ($q = d\psi_{\text{toroidal}}/d\psi_{\text{poloidal}}$), B is the toroidal magnetic field [tesla] at major radius R , p is the plasma thermal pressure, χ_i is the ion thermal diffusivity [meter²/second], χ_i^{neo} is the neo-classical ion thermal diffusivity derived by Chang and Hinton,¹¹ D is the particle diffusion rate, and v is the inward pinch velocity.

This transport model has the virtue of being a simple model which is found to simulate a wide variety of experimental data. For the simulations presented here, the constant multiplier in the electron thermal diffusivity was deliberately increased in order to keep the computed global energy confinement time at least 10 to 20% below the Kaye-Goldston scaling. Using the particular choice of thermal diffusivity in Eq. (1), which scales like T^2 , it was found that the computed energy confinement time divided by Kaye-Goldston¹² scaling (power^{-0.58} form) drifted by no more than about 30% over a wide range of conditions (ignition, centrally peaked profiles, sawtooth oscillations, etc.) after an initial transient. The Singer-Ku¹³ model with T_e to the first power, which also calibrated well against experimental data, was not used because it did not track as well against Kaye-Goldston scaling under the conditions in use here.

The particle diffusion coefficient was deliberately chosen to be small so that the convection of energy resulting from particle diffusion would be small enough not to influence global energy confinement. The inward particle pinch was chosen together with the particle diffusivity to produce a Gaussian particle distribution in steady state (in the absence of sawteeth) with $n_{e0}/\langle n_e \rangle = 4.0$ and a half-width equal to 0.413 times the plasma half-width.

A Kadomtsev reconnection model¹⁴ is used to model sawtooth oscillations with a prescribed fixed period. At the end of each period, a sawtooth crash can occur only if the magnetic q -value is less than 1.0 somewhere within the plasma. Then the helical flux $\psi_{\text{helical}} = \psi_{\text{toroidal}} - \psi_{\text{poloidal}}$ is computed and redistributed according to the Kadomtsev model¹⁴ in order to find the new poloidal flux and corresponding poloidal magnetic field and current density. Throughout the mixing region (i.e., the region throughout which the initial helical flux is nonmonotonic), the particle densities and temperatures are flattened in such a way as to conserve total particle numbers and energy. Magnetic energy is transferred to the electrons.

II. The Effect of Sawtooth Delay on Ignition

Figures 2 to 9 show the results of the best example found to date of sawtooth delay and ignition at low energy confinement time (shown at the top in the three-dimensional plots) compared with the results of a more typical simulation with 0.1-second period sawtooth oscillations present from beginning to end (shown at the bottom in the three-dimensional plots). Large sawtooth oscillations are delayed by the following combination of procedures:

- The initial central q -value is 1.2 over 30% of the plasma half-width in the simulation shown at the top compared to 0.98 in the simulation shown at the bottom (where the first sawtooth was triggered at 0.05 seconds). In a wide variety of simulations, it was found to be essential to catch the plasma before large (broad) sawtooth oscillations had become established. It may be possible to reverse small sawteeth, but it was found to be very difficult to stop sawteeth with a 70% mixing radius once they had begun.
- A deuterium pellet at $t = 0.02$ seconds quickly followed by a tritium pellet at $t = 0.04$ seconds were injected before the plasma became energetic enough to prevent them from reaching the center. Each spherical pellet, with 0.2 mm radius, had a 2.0 km/second velocity aimed at the magnetic axis. A Milora-Foster ablation model was used.¹⁵ The pair of pellets raised the volume-averaged density from 6.1×10^{19} to 4.8×10^{20} ions per cubic meter, which subsequently decayed to $4.4 \times 10^{20} \text{ m}^{-3}$ after 2.0 seconds. The central ion density was raised from 8.7×10^{19} to 6.1×10^{21} , but rapidly decayed to 2.0×10^{20} particles per cubic meter as shown in Fig. 3. The pellets penetrate far enough to cool the center of the plasma, leaving a hollow temperature profile and starting the process of maintaining a slightly hollow current profile. Unfortunately, once the plasma becomes more energetic, pellets no longer penetrate well enough to densify and cool the center of the plasma (at least, according to this simulation model). Consequently, after initializing with pellets, the centrally peaked density profile was subsequently maintained in this simulation by using an anomalous inward particle pinch. The Ware pinch is feeble under these conditions.

Note that the large sawteeth in the simulation shown at the bottom, broaden the density profile to the extent that the central ion density oscillates between 7.1 and $7.9 \times 10^{20} \text{m}^{-3}$ while the volume-average ion density is held at $4.5 \times 10^{20} \text{m}^{-3}$ with gas puffing (50% deuterium and 50% tritium). The effect of these large sawteeth can also be seen in the last 0.6 seconds of the simulation shown at the top.

- 20 MW of auxiliary heating was applied between $0.3 < r/a < 0.7$ (peaked at $r/a = 0.5$) from $t = 0.05$ to $t = 2.0$ seconds in the simulation shown on the top while the same power was applied over a broad region (half-width equal to a quarter of the width of the plasma) centered at the magnetic axis from $t = 0.0$ to $t = 3.0$ seconds in the simulation shown at the bottom. Although 75% of the heating power was applied to the ions and 25% to the electrons, the equipartition time is so short that the electron and ion temperatures remain almost identical. Off-axis heating proved to be the most effective means for broadening the current profile and delaying the onset of sawtooth oscillations over the longest time span in the simulations. The current profile is actually made hollow by the off-axis heating, as shown in Fig. 4 at the top. It can be seen in this figure, that small sawtooth oscillations develop in the center of the plasma after 2 seconds, apparently driven by the neoclassical current density peaking at the magnetic axis. These small sawteeth do little harm to the ignition.
- The total plasma current is ramped from 7.0 to 10.0 MA during the first second of the simulations shown at the top. This aids in the delay of large sawteeth, but is not as effective as off-axis heating in the long run.

The combined effect of pellets, off-axis heating, and current ramp can be seen most dramatically in the plot of magnetic q-value as a function of flux surface and time as shown in Fig. 5 at the top. Just after the pellets are injected, the central q-value rises sharply and then slowly decays over 2 seconds. The off-axis heating, aided initially by the current ramp, produces a low broad peak away from the magnetic axis. Eventually, the q-value drops below unity nearly half-way between the magnetic axis and the edge,

resulting in an abrupt broad sawtooth crash which sharply reduces the centrally peaked density and temperature.

It is important to turn off the off-axis auxiliary heating before it drives the q -value below unity. Figure 6 shows a detail of the q -value as a function of flux surface half-width for a selection of times during the sawtooth delay simulation. It can be seen that the q -value is nonmonotonic over a narrow range of values which do not involve low-order mode rational surfaces (and, consequently, will probably not excite large double tearing modes). If the off-axis heating were left on much longer than two seconds, the q -value would be driven below unity more rapidly and broad sawtooth oscillations would occur earlier in this simulation, reducing the chances for ignition. Many simulations were tried in which broad sawteeth started just at or before the time of ignition, before a more optimum combination of off-axis heating, pellets, and current ramp was found to delay the onset of broad sawteeth until well after ignition had occurred. In the case presented here, the auxiliary heating was turned off just as the plasma ignited and the q -profile remained between 1.0 and 1.2 over a broad region in the center of the plasma for 3.4 seconds.

The confinement model was chosen to keep the global energy confinement time at or below Kaye-Goldston scaling¹² throughout the simulation, as shown in Fig. 7. Using

$$1/\tau_{KG}^2 = 1/\tau_{OH}^2 + 1/\tau_{aux}^2, \quad (5)$$

with

$$\tau_{OH} = 0.07 n_{e20} a_m R_m^2 q_{cyl} \quad (6)$$

$$q_{cyl} = \frac{5a_m^2 B_{tesla}}{R_m I_{MA}} \frac{1 + \kappa^2}{2}, \quad (7)$$

two forms of the Kaye-Goldston L-mode scaling¹² are used for τ_{aux} :

$$\begin{aligned} \tau_{aux}(\text{Power}^{-0.58}) = & 0.0553 \kappa^{0.28} B_{tesla}^{-0.09} I_{MA}^{1.24} n_{e20}^{0.26} a_m^{-0.49} R_m^{1.65} \\ & \times P_{MW}^{-0.58} (A_1 A_2 / 2)^{0.25} \text{ seconds} \end{aligned} \quad (8)$$

or

$$\begin{aligned} \tau_{aux}(\text{beta}^{-1.38}) = & 0.01934 \kappa^{-0.714} B_{tesla}^{-2.98} I_{MA}^{2.95} n_{e20}^{0.62} a_m^{-3.93} R_m^{2.55} \\ & \times \beta_{\%}^{-1.38} (A_1 A_2 / 2)^{0.25} \text{ seconds.} \end{aligned} \quad (9)$$

Here, $\kappa = b/a$ is the elongation, n_{e20} is the volume-averaged electron density in units of 10^{20}m^{-3} , a is the plasma half-width in meters, and A_1 and A_2 are the atomic masses of the hydrogenic species used (deuterium and tritium). These two forms of τ_{aux} should be equivalent in steady state. However, they are observed to differ by up to 50% with all the dynamics of the discharges being simulated here, even before sawteeth cause the energy confinement time to oscillate as shown near the end of Fig. 7 (top).

The time histories of total beta and heating power are shown in Fig. 8. The plasma was just barely ignited at $t = 2$ seconds, at which time the global energy confinement time was 0.2 seconds. In order to achieve ignition with such a low energy confinement time, the plasma had to be producing 105 MW of alpha heating power. The alpha heating power required for ignition could be substantially reduced if the energy confinement time were higher. In this simulation, there is a gradual reduction of alpha heating power and total beta (which includes the contribution from fast alphas) as small sawtooth oscillations set in and the central density is reduced slightly. Plasma ignition is then extinguished when the broad sawtooth oscillations set in after $t = 3.4$ seconds.

The volume-averaged beta within each flux surface, shown in Fig. 9, is very centrally peaked in the delayed sawtooth simulation (top), since both density and temperature profiles are centrally peaked before the broad sawteeth set in. Although the total volume-averaged beta remains below the Troyon limit¹⁷ (about 6%) throughout the ignition and burn, there are preliminary indications¹⁸ that the profile is ballooning-mode unstable over most of the center of the plasma, where the magnetic shear is low in these simulations. While centrally peaked pressure profiles are conducive to ignition, and a broad region of low magnetic shear is dictated by the sawtooth model, ballooning modes or low shear interchange modes over the central region of the plasma may force the pressure profile to be broad. The Troyon limit¹⁷ was computed using optimized broad pressure profiles. Centrally peaked high beta profiles and the consequences of ballooning modes in tokamaks, however, have yet to be investigated experimentally.

From a series of simulations under similar conditions, it is found that fusion power production and ignition depend quite sensitively on the plasma density and its profile. For example, holding the volume averaged electron

density $\langle n_e \rangle$ fixed at $5.0 \times 10^{20} \text{ m}^{-3}$, but reducing the inward pinch relative to diffusion va/D (dimensionless) from the value 5.744 used in the simulations shown in Figs. 2 through 9 to $va/D = 3.6$, reduces the alpha power production from nearly 140 MW to less than 75 MW for a barely ignited plasma. Further reducing va/D to 1.44 reduces the alpha power production to less than 35 MW and prevents ignition. The density profile becomes flatter with each reduction of the inward pinch, since the density is maintained by gas puffing after the initial transient. With even a flat density profile, however, alpha power production and ignition can be restored in these simulations by raising $\langle n_e \rangle$ above $8.0 \times 10^{20} \text{ m}^{-3}$. The characteristic features of sawtooth delay and centrally peaked temperature profiles remain essentially unchanged as the density and its profile are changed.

III. Conclusions

Peaked density and temperature profiles may be needed to achieve ignition in the Compact Ignition Tokamak if the energy confinement time scales pessimistically low. Such peaked profiles can be maintained only if sawtooth oscillations with a broad mixing region are delayed or have a very long sawtooth period. A combination of pellet injection, off-axis heating, and current ramp was used in this simulation together with an inward particle pinch in order to achieve ignition with one of the more pessimistic confinement scalings supported by experimental evidence. Current drive, the accumulation of impurities, and different transport conditions (such as the H-mode) are alternative ways to control the extent and period of sawtooth oscillations, which need to be explored.

In this simulation, pellets were injected near the beginning of the discharge, while the plasma was relatively cool and tenuous. It does not appear to be feasible to inject pellets once the plasma is hot and dense. Nor is it feasible on CIT to use neutral beams to fuel the center of the plasma, to maintain a centrally peaked density. Present experimental evidence indicates that an anomalous inward particle pinch appears to play an important role in particle transport but, aside from altering particle transport with pellets and edge pumping, it is not yet clear if this inward pinch can be controlled to our advantage.

Acknowledgments

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Figures

FIG. 1. Cross section and typical flux coordinates for the Compact Ignition Tokamak CIT-1 design.

FIG. 2. Ion temperature (vertical axis) as a function of half-width (horizontal axis) and time (receding axis) for the delayed sawtooth simulation (top) compared to the reference simulation (bottom).

FIG. 3. Ion density (deuterium + tritium, along vertical axis) as a function of half-width (horizontal axis) and time (receding axis) for the delayed sawtooth simulation (top) compared to the reference simulation (bottom).

FIG. 4. Flux-surface-averaged current density (along vertical axis) as a function of half-width (horizontal axis) and time (receding axis) for the delayed sawtooth simulation (top) compared to the reference simulation (bottom).

FIG. 5. Magnetic q -value (along vertical axis) as a function of half-width (horizontal axis) and time (receding axis) for the delayed sawtooth simulation (top) compared to the reference simulation (bottom).

FIG. 6. Top: Magnetic q -value as a function of half-width for the delayed sawtooth simulation. Bottom: Profile of ICRH heating power.

FIG. 7. Top: Energy confinement time as a function of time during the delayed sawtooth simulation. Bottom: Ratio of energy confinement time to Kaye-Goldston confinement time in the form $(\text{heating power})^{-0.58}$ and $(\beta)^{-1.38}$.

FIG. 8. Top: Volume-averaged β (in %) as a function of time during the delayed sawtooth simulation. Bottom: Total heating power (in MW) as a function of time for this simulation. The heating power is broken down into (1) alpha heating, (2) auxiliary heating (20 MW up to 2.0 seconds), and (3) ohmic heating.

FIG. 9. Volume-averaged beta (along vertical axis) as a function of half-width (horizontal axis) and time (receding axis) for the delayed sawtooth simulation (top) compared to the reference simulation (bottom).

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