Recent Experimental Results on the Repetitive Compact Toroid Accelerator at UC Davis

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Abstract. This article reports on the acceleration dynamics of a compact toroid plasma configuration in a background hydrogen gas. The acceleration dynamics are investigated experimentally using magnetic probes and chordal interferometry. These measurements are then compared to two-dimensional simulations that show good agreement with experiments. The experimental measurements indicate that the velocity and field strength initially increase as a function of accelerator voltage, however, at higher voltages the compact toroid velocity ceases to increase with increased accelerator voltage. In our investigation, we examine the "blowby" effect along with additional processes such as mass accumulation and charge exchange as potential mechanisms contributing to the stagnation of the compact toroid's velocity.

1. Introduction

Central fueling of a magnetic fusion reactor has been shown theoretically to improve the overall fusion efficiency of the reactor [1]. Accelerated spheromak-like compact toroids (SCTs) are a promising way to centrally fuel a fusion reactor. The penetration of compact toroids into the central regions of tokamak plasmas has been investigated both theoretically and numerically [2-5]. Experiments on the Tokamak De Varnnes [6], as well as smaller experiments at the University of California at Davis [7,8] and the California Institute of Technology [9], have also investigated compact toroid fueling and helicity injection on tokamaks. In order for compact toroid fueling to be viable for a fusion reactor, the injector must operate in an efficient repetitive mode with the repetition rate comparable to or greater than the particle confinement time of the fusion plasma. The SCT accelerator at UC Davis (CTIX) operates in a repetitive mode using a passive switching method [7]. In this article, we report on the acceleration dynamics of the CTIX accelerator when operated with a gas fill.

2. Experimental Measurements on the CTIX Accelerator

The experiments described in this article were performed on the compact toroid injection experiment (CTIX) [7] operated by the University of California at Davis. This rep-rated compact toroid plasma accelerator, shown in Fig. 1, can form and accelerate compact toroids at a rate of 0.1 Hz. The compact toroids are initially created near the gas valve in the formation section. The compact toroid is then pushed into the acceleration section where it is driven to high speeds. The CTIX is capable of accelerating compact toroid plasma configurations to velocities in excess of $2x10^5$ m/s in a distance less than 1.5 m; thus imposing an acceleration of over 10^9 times the earth's gravitational acceleration.

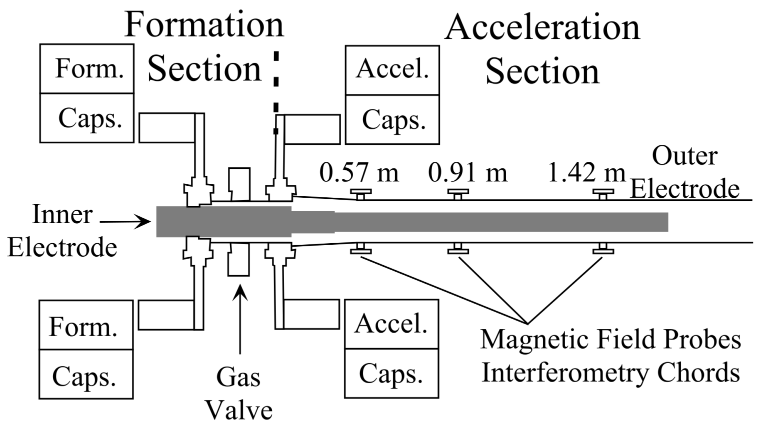

Figure 1. Schematic of the compact toroid injection experiment (CTIX). The compact toroid is accelerated between the inner and outer electrodes. Diagnostics placed at the three locations indicated measure the time-integrated magnetic field, line-integrated electron density and visible emission.

The measurements described below were taken at three separate locations along the accelerator at 0.57 m, 0.91 m and 1.42 m, as shown in Fig. 1. These three axial locations are in the acceleration section of the CTIX. Time-dependent magnetic field measurements of the poloidal and toroidal magnetic fields near the outer electrode of the CTIX accelerator were obtained using perpendicular magnetic loops. The time-dependent line-integrated electron density present in the compact toroid was measured with a HeNe interferometer system operating at 633 nm. Additional diagnostics recorded the voltage and current of the accelerator and formation sections, as well.

Fig. 2 shows the measured full-width-at-half-maximum (FWHM) and the peak poloidal field of the compact toroid at a distance 1.42 m along the accelerator as a function of accelerator voltage. In Fig. 2, the poloidal field maximum and FWHM are represented by black squares and gray diamonds, respectively. Simulations are represented by the gray and black line for the FWHM and maximum of the poloidal, respectively. The error bars represent the standard deviation of twenty shots taken at each voltage setting. This figure shows a large decrease in the FWHM of the poloidal field as the accelerator voltage is increased. This decrease in the FWHM of the compact toroid's poloidal field occurs as the compact toroid undergoes a transition from free expansion at low accelerator voltages to compression at higher accelerator voltages. The FWHM of the poloidal field at 0.91 m and 1.42 m reaches a minimum value close to 10 kV and begins to increase slowly at higher voltages. The error bars also indicate a much greater reproducibility at higher accelerator voltages as evidenced by the reduced standard deviation in the shots.

Fig. 3 represents the average velocity of the compact toroid. The average velocity is calculated using the poloidal field measurements at the three different locations along the compact toroid. The average velocity is calculated by dividing the probe separation by the time difference in the poloidal field maximum. This measurement gives the average velocity of the compact toroid between the probe locations at 0.57 m and 0.91 m and between the probes at 0.91 m and 1.42 m. In Fig. 3, the experimentally determined mean velocity of the compact toroid is represented by black circles, where the error bars again represent the standard deviation. Two-dimensional magnetohydrodynamic (MHD) simulations are represented by the diamonds, square and

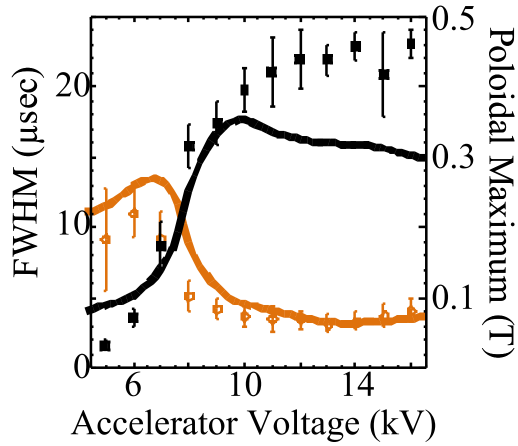

Figure 2. Comparison between experimental measurements and simulations of the compact toroid's poloidal magnetic field at 1.42 m. Simulations are denoted by gray and black lines while experimental measurements are denoted as gray circles and black squares for the FWHM and the field maximum, respectively.

triangles. The velocity increases linearly with accelerator voltage until the accelerator voltage reaches 11 kV. At this point the velocity begins to decrease with increasing accelerator voltage.

3. Discussion

The velocity of the compact toroid shown in Fig. 3 reaches a maximum at an accelerator voltage of approximately 12 kV and then begins to decrease at higher voltages. When the accelerating magnetic pressure behind the compact toroid becomes larger than the internal pressure of the

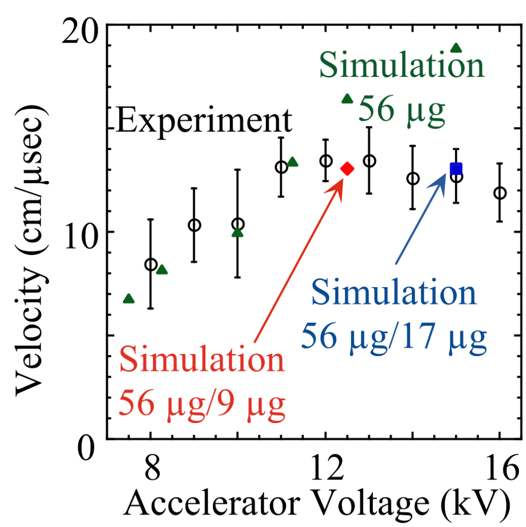

Figure 3. Comparison of the compact toroid's velocity between experiment and simulations. Simulations are represented by the diamond, square and triangles while the experimental mean is denoted by the black circles, respectively. The diamond and square represent a 56 μg compact toroid accelerated through 9 μg and 17 μg of plasma uniformly distributed throughout the accelerator section, respectively.

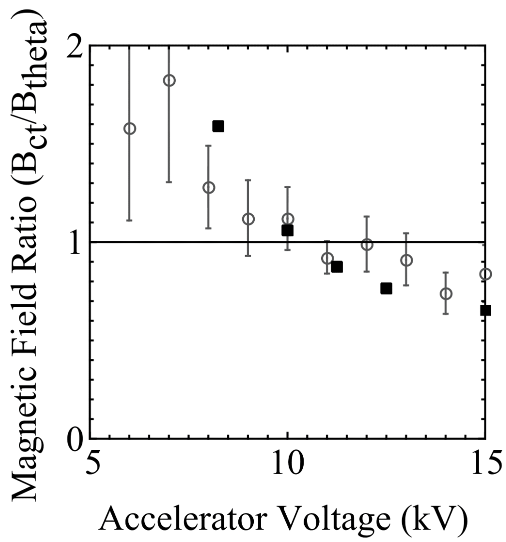

Figure 4. Comparison of the ratio of the compact toroid's internal magnetic field to the acceleration field between experiment and simulations. Simulations are represented by the solid black, squares and experiments by the black circles.

compact toroid, "blowby" [10,11] of the accelerating fields can occur. Fig. 4 shows the ratio of the compact toroid's internal magnetic field to the accelerating field behind the compact toroid. Both the simulations, black squares, and the experiments, open circles, indicate that when the accelerator voltage reaches 11 to 12 kV, the magnetic pressure pushing the compact toroid becomes larger than the compact toroid's internal magnetic pressure. Fig. 3 shows that acceleration of the compact toroid is reduced in the simulations at higher voltage, but that the velocity continues to increase with accelerator voltage. In the experiments, however, the compact toroid begins to slow down at higher voltages.

The compact toroid can be slowed down by a number of processes. One of the processes that can slow down the compact toroid is the accumulation of gas. This gas can originate either from the formation gas jet or from the walls of the electrodes themselves. As the compact toroid propagates along the accelerator, this gas or plasma is swept up by the compact toroid introducing a drag effect. The compact toroid can also lose momentum without changing the mass of the compact toroid due to charge exchange with gas that can again originate from the gas jet or be emitted from the walls. The compact toroid can also slow down if the acceleration current at higher voltages is reduced by current flow from the outer to inner electrode via the slow moving plasma behind the compact toroid.

The axial profile of the accelerating current is determined by comparing the toroidal field measurements at 0.57 m and 0.91 m at a time when the compact toroid has passed both probe locations. These measurements indicate a reduction in the current between these two probe locations of approximately 10 percent, however, this difference does not increase with accelerator voltage. Because there is no voltage dependence to this current loss, this mechanism can not explain the results seen in Fig. 3.

Interferometry measurements taken at 1.42 m and 0.91 m along the accelerator indicate an electron density increase as a function of accelerator voltage. The MHD simulations shown in Figure 3 as the solid triangles represent the acceleration of a compact toroid with a mass of 56 μg given an initial velocity of $5x10^4$ m/s. When additional plasma is uniformly added to the accelerator section in front of the compact toroid, the simulations reproduce the velocity behavior of the compact toroid. The mass increase required in the simulations is approximately linear with accelerator voltage above 11 kV. These simulation points are shown in Fig. 3 as the diamond at 12.5 kV and the square at 15 kV. The increase in electron density seen by the interferometers, however, could also result from the ionization of impurities within the compact toroid to a higher charge state without changing the mass of the compact toroid.

4. Summary

This article reported on the acceleration dynamics of the compact injection experiments. The time-dependent magnetic field and velocity measurements were compared with two-dimensional MHD simulations of the compact toroid acceleration process. The experimental measurements of the FWHM of the poloidal magnetic field were observed to decrease with increased accelerator voltage to a minimum value of 2 μsec. Concurrently the peak poloidal values were shown to increase to a maximum value of 0.47 T. The compact toroid velocity was observed to increase to a value of $1.4x10^5$ m/s at an accelerator voltage of 12 kV. This maximum was shown to coincide with the point at which “blowby” of the acceleration field would be expected. At higher voltages, the velocity decreased further. This could be attributed to either mass accumulation or charge exchange as discussed above.

This work was performed under the auspices of the U.S. Department of Energy by the University of California at Davis under contract No. DE-FG03-90ER-54102 and DE-FG03-97ER-54434.

Acknowledgements The authors would like to acknowledge discussions with J. H. Hammer and G. L. Schmidt.

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