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First Observation of the High Field Side Sawtooth Crash and Heat Transfer during Driven Reconnection Processes in Magnetically Confined Plasmas.

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High resolution (temporal and spatial), two dimensional images of electron temperature fluctuations during sawtooth oscillations were employed to study driven reconnection processes in magnetically confined toroidal plasmas. The combination of kink and local pressure driven instabilities leads to an "X-point" reconnection process that is localized in the toroidal and poloidal planes. The reconnection is not always confined to the magnetic surfaces with minimum energy. The heat transport process from the core is demonstrated to be highly collective rather than stochastic.

Topological changes of the magnetic field configuration in plasmas, i.e. the magnetic reconnection process, have been observed in laboratory plasmas [1], solar flares [2], and interstellar space [3]. This paper concerns the sawtooth oscillation [4], which is a repetitive benign disruptive behavior in which a nested magnetic field ruptures and stored plasma energy abruptly bursts out to the periphery. This phenomenon is extremely important in toroidally confined plasmas because amelioration of the non-benign disruptive behavior will enhance the success of the next step magnetic fusion device (ITER; Latin for 'The way') and future fusion power plant to contain a sustained reaction. Numerous physical models have been developed to explain the changes in the magnetic topology, of which most have focused on developing an understanding from first principles of the underlying magnetic reconnection process. In particular, the recent observation of sawtoothing radio frequency emissions from solar flares [5] suggests that the physical mechanism underlying this behavior may be universal in current carrying toroidal plasmas. Consequently, understanding of the sawtooth oscillation of current driven toroidal plasmas will be highly beneficial for solar and interstellar physics as well for optimizing the control of magnetic fusion devices.

The sawtooth oscillation in toroidal high temperature plasmas was discovered in 1974 [4] and it is known as the repetitive growth and decay of the core plasma pressure (and/or core current) through a driven magnetic reconnection process as shown in Fig.1. A variety of theoretical models have been developed and experimental studies have been conducted aimed at explaining the driven reconnection process during the sawtooth oscillation and an excellent review is available in Ref. [6]. The full reconnection model [7] suggests a complete exhaust of plasma pressure and current density through an "X-point" reconnection process along the entire toroidal direction initiated by the pressure driven instability of *m/n=1/1* mode, where the plasma pressure ($p = \sum_{j=i,e} n_j T_j$) consists of particles (electrons and ions) at their corresponding temperatures and *m* and *n* are poloidal and toroidal mode numbers, respectively. The characteristic time scale is referred to as the reconnection time ($\tau_c \approx \frac{1}{2}\sqrt{\tau_A^* \cdot \tau_\eta}$), where τ_A^* is modified Alfven transit time and τ_η is resistive diffusion time and the typical value is ~700 *microseconds* for the plasma parameters used in this experiment. Another theoretical model is the 'quasi-interchange' model [8] where the cooler plasma convectively flows into the plasma core and the hot spot evolves into a crescent shape due to the magnetic shear of the *m/n/=1/1* mode without any magnetic reconnection process. Experimental verification of such a distinctively different evolution of the hot spot /island between the full reconnection model and the quasi-interchange model has not been conclusive due to the lack of accurate 2-D experimental tools [9]. However, in current density profile measurements [10, 11], only slight changes of current density were observed while the reconnection time was much faster than expected on theoretical grounds. This discrepancy motivated further modeling of the driven reconnection process. Observation of a localized electron temperature bulge [12, 13] during the sawtooth crash motivated researchers to introduce a model based a finite pressure effect on the m/n=1/1 mode [14] at the “bad curvature” side of the magnetic surface (low field side in Fig.1) and a pressure driven ballooning instability [15, 16] combined with global stochasticity [14, 15, 16] of the field lines to explain the observed little change of the core current density in a finite beta plasmas, where beta is the ratio between plasma pressure (*p*) and magnetic energy ($B^2/2\mu_o$). In moderate beta plasmas, such as those corresponding to the experimental results discussed here, the level of the ballooning instability and global stochasticity of magnetic field lines strongly coupled to the pressure surfaces is expected to be moderate compared to those at high beta plasmas.

All models developed to explain the sawtooth oscillation are still based on numerous assumptions, and thus there is a need to compare them with precise experimental results. In particular, experimental evidence is required concerning the specifics of the driven reconnection process such as undisputable images of the hot spot and/or island, type of reconnection process (“X-point” or “Y-point” [16, 17]), “pressure finger” in the ballooning model, evidence of stochasticity of the magnetic field lines and the physical dimensions of the reconnection zone to identify whether the process is full or partial reconnection.

In order to reconcile the discrepancies between experiments and theoretical models and to improve the present theoretical understanding of the fundamentals of the driven reconnection process, one requires higher dimensional insight into the plasma dynamics in the core of magnetically confined plasmas than is available from conventional 1-D diagnostics. Fortunately, such information has recently become available through the use of a two-dimensional (2-D) electron cyclotron emission imaging (ECEI) system [19, 20] developed for the Toroidal Experiment for Technology Oriented Research (TEXTOR) tokamak plasma; TEXTOR is in the Forschungszentrum Jülich, Germany.

The TEXTOR tokamak plasma has a circular shape with a major radius of 175 cm and minor radius of 46 cm. The range of toroidal magnetic field in the present work was 1.9 - 2.4 T and the corresponding plasma current was <305 kA. The H^+ plasma is heated with energetic neutral beams (D_0, ~50 keV, up to 3 MW) in order to maximize the temperature fluctuation of the sawtooth oscillation as well as to control plasma rotation (by varying the ratio of co- to counter- injection with respect to the direction of plasma current. The key plasma parameters were as follows: the central electron density and temperature range from 1.5 to 2.5 x 10^{19} m^{-3} and from 1.2 to 1.6 keV, respectively. The corresponding peak toroidal beta is ~1.0 % and the average poloidal beta is between 0.3 and 0.5. The toroidal rotation of the plasma varied from ~1 x 10^4 m/s to ~8 x 10^4 m/s. The speed of a thermal electron is ~6 x 10^7 m/s. The Alfven and ion acoustic speeds are 5 x 10^6 and 7 x 10^5 m/s., respectively. Using plasma parameters close to the q~1 surface, the calculated characteristic reconnection time (τ_c) is ~700 μs.

In magnetically confined plasmas, the gyro motion of electrons results in emission of radiation at the electron cyclotron frequency, $\omega_{ce} = \frac{eB}{m_e}$, and its harmonics, where B is the applied magnetic field strength, e is the electron charge, and m_e is the electron mass. In optically thick plasmas where the electron density and temperature are sufficiently high, the radiation intensity becomes equivalent to that of black body emission [20], where the intensity of the emission is directly proportional to the local electron temperature. In toroidal plasmas, the ECE frequency has a spatial dependence due to the radial dependence of the applied toroidal magnetic field [$B(R) = \frac{B_0 R_0}{R}$], where R_o and B_o are the geometric center and the magnetic field strength at the center of the plasma, respectively. The fundamentals of the ECE process are well established and have been routinely utilized to measure local electron temperatures in magnetically confined high temperature plasmas [20]. For 2-D imaging, the single antenna of a conventional 1-D radiometer [20] is replaced by a vertically distributed array of antennas as shown in Fig.3 of Ref. [22], which images the plasma layer with an optical system similar to that of a camera with zoom lens; thus radial resolution is maintained from the ECE frequency discrimination while vertical resolution is provided by the imaging optics. The combined multichannel detection technique is dependent on sensitive 1-D arrays, employing advances [18] in array technology and state-of-the-art wide band millimeter wave and intermediate frequency electronics fabrication techniques. The sampling area of the image at the focal plane is 16 cm (vertical) x 8 cm (radial) and the vertical resolution is determined by the optical element and is ~2 cm for each pixel and the radial resolution is ~1 cm across the core of the tokamak plasma (total 128 channels). The time resolution is primarily limited by the digitizer and the fastest time scale can be up to 5 *microseconds*. Intensive laboratory testing was performed during the course of development which, together with a detailed system description, is given in other references [17, 18]. The fluctuation quantities are relatively calibrated to the averaged value obtained with a long integration time and the intensity of the images is represented by $\delta T_e/<T_e>$, where T_e is the electron temperature, $< >$ is the time average, δT_e is the fluctuation level ($= T_e - <T_e>$), and $<T_e>$ is constant for the duration of many sawtooth oscillations. As demonstrated in a previous study of sawtooth physics by 1-D ECE [12], the plotting of only the fluctuating temperatures (and subtracting the non-changing, time-averaged temperature) simplifies the evaluation of the heat flow during the crash.

It is instructive to show the measured 2-D images of the electron temperature fluctuations together with the schematic of the temperature profile change during the reconnection time through a composition of three images as shown in Fig. 1. The composite image, based on an average of ~10 almost identical sawtooth oscillations, demonstrates that the behavior of the reconnection phenomena appears to be consistent with the full reconnection model and experimental results [7, 12, 13] on a global scale, where the core temperature profile is flattened during the reconnection process and the transported heat accumulates outside of the inversion radius. The inversion radius, illustrated in Fig. 1, is the radial position where the change of the temperature is minimum during the reconnection process. The hot spot, partially shown in whitish green color (frame 1), corresponds to a peaked electron temperature profile within the inversion radius (indicated as a double white line). The core electron temperature profile suddenly flattens (the direct reconnection process was not observed at the view position) and a cold spot shown as a bluish black color resides in the zone previously occupied by the hot spot (frame 2). The heat removed from inside the inversion radius reappears at the outside of the inversion radius from the bottom of the low field side (frame 2) in an asymmetric pattern. Accumulated heat eventually becomes symmetric (frame 3) and fades away through a diffusive process.

There are many sawtooth oscillations in a single discharge (one sawtooth period is ~15 ms whereas the entire discharge duration is ~5 *seconds*), each particular reconnection event may or may not occur within the field of view of the ECEI instrument, due to the random toroidal/poloidal phase of the localized reconnection region along the helical field structure. A representative sequence of 2-D images illustrating the full view of the reconnection process observed at the low field side is shown in Fig. 2. This evaluation has nothing to do with the reproducibility of the reconnection process, but rather concerns the fact that the phase of each reconnection event at the view position is primarily dictated by the timing of the local nature of the reconnection process and the toroidal rotation of the entire plasma. The temperature perturbation in frame 1 is still rather symmetric, but in later frames a clear distortion of the hot spot at the low field side becomes apparent. The growth of a sharp temperature point shown in frames 3 and 4, which even crosses the inversion radius, is reminiscent of the theoretical reconnection process based on the "pressure finger"- ballooning mode discussed in Refs. [15, 16]. However, these theoretical models have been primarily developed for high beta plasmas and thus may not be directly applicable for low beta plasmas, such as the present experiment in which a moderate growth of the ballooning mode and a moderate level of stochasticity of field lines would be expected. From the images in Fig. 2, it appears that the heat punches through the "pinhole" and the reconnection zone grows as the heat transport is increased. The size of the reconnection zone increases to ~15 cm and the heat transported outside the inversion radius is distributed along the poloidal and toroidal planes in a coherent manner. Since the time scale of direct electron thermal velocity is on the order of *nano-seconds* and the progression of the images spans tens of *micro-seconds*, it is reasonable to assume that the transient heat flow follows the local magnetic field lines. Initially, the heat flow forms an 'X-point' shape, which resembles that of the full reconnection model. It appears that the flow of heat is highly collective along the field lines. The spatial broadening of the heat outside the inversion radius shown in frames 6 and 7 can account for the toroidal spread of the heat, since the time it takes for electrons to complete one transit of the torus is on the order of a *micro-second*. At the end of the reconnection phase, island is fully established and the temperature perturbation recovers symmetry as shown in frame 8. It should be noted here that although it is the absolute temperature that is related to the magnetic field topology, the temperature fluctuation contour plots and the associated heat flow are also a good indication of an opening in the magnetic surfaces.

In a second experimental campaign, the sample volume of the imaging system was moved to the "good curvature" side of the magnetic surface (high field side in Fig. 1) in order to explore reconnection phenomena there. Theoretical models and experimental observations so far suggest that the pressure driven ballooning mode instability is likely to find a minimum magnetic field region (at the low field side of the inversion radius) to release energy during the reconnection phase. Again, several tens of images of the sawtooth oscillations were scrutinized due to the local nature of the reconnection process and plasma rotation. It was found that the reconnection can occur at the high field side with the entire process quite similar to that at the low field side. The progressive detailed images of the reconnection process at the high field side are illustrated in Fig. 3. In the early stages, the hot spot is symmetric as shown in frame 1. In frame 4, a distortion of the hot spot is visible and a sharp temperature point is formed, but does not lead to a reconnection. As the pointed temperature surface is retreating, moderate swelling of the temperature (which is indicative of a growing kink instability or finite pressure effect on m/1n=1/1 mode) is shown in frame 5. In frame 7, a larger sharp temperature point with a strong swelling of the hot spot (strong kink) pushes the sharp temperature point beyond the inversion radius and heat starts flowing out in a collective fashion once the surface is opened. The first, but not complete, onset of a reconnection (frame 4) where a sharp temperature point is formed but does not lead to reconnection, could be attributed to lack of global pressure (energy from the kink or pressure bulge). However, the second attempt (frame 7) succeeds in opening the magnetic field and the dimension of the opening starts with a small hole and grows up to ~10 cm which is similar to the behaviors in the low field side. As the heat is flowing out, the nested field lines from the core (cold spot) push the remaining heat from the rear as illustrated in frames 8-11. The time evolution of hot spot and island formation resembles a flattening process of the pressure profile proposed by the full reconnection model [7]. As the heat is removed from the core, a closed field line topology is established again and the poloidal symmetry is recovered as shown in frame 12. The observed sharp point in temperature again resembles the ballooning mode, but should be inhibited at the high field side and the magnitude of the sharp point should be moderate at this value of plasma beta. The entire sequence of the heat flow pattern is quite consistent with that of the low field case.

The toroidal extent of the reconnection zone was determined from the images of the sawtooth crash in rotating plasmas, where the rotation speed is estimated from the transit time of the hot spot from pre-cursor oscillations. During the reconnection phase, the transit time of the hot spot crossing the inversion radius is equivalent to the toroidal extent of the reconnection zone. This fact alone does not prove that the toroidal extent of the reconnection zone is localized or that it extends all around the torus along the magnetic pitch. Often, the hot spot suddenly moves away from the view position when it is expected to cross the view at the moment of reconnection. This is a good indication that the reconnection process is occurring somewhere else and leads to the conclusion that the toroidal extent of the reconnection zone is localized. Accurate estimation of the toroidal reconnection zone is limited due to the current image size, but can be roughly estimated to be ~3.3 *m* (larger than _ and less than _ of the toroidal circumference). This is consistent with the observation that multiple toroidal views of x-ray tomography in other experiments exhibit a fading hot spot away from the reconnection position [22]. The experimentally determined reconnection time (500 ~700 *microseconds*) based on the beginning time when the formation of the island is first observed (precursor) and the ending time when the island is fully established in the core, is consistent with the characteristic reconnection time (τ_c) discussed in earlier section. However, the first hint of heat flow through the inversion radius is routinely observed at the last stage of precursor period. This experimental observation suggests that there are additional physical mechanisms associated with the simple reconnection model or simply that the reconnection occurs in a different critical time. The experimentally determined reconnection time based on the first hint of heat flow through the inversion radius is typically less than ~100 *microseconds*.

2-D images of electron temperature fluctuations during sawtooth oscillations provided new insights into the heat transfer process during the driven magnetic reconnection process of the sawtooth oscillation in current carrying toroidal plasmas with a strong guiding magnetic field (toroidal field outside the inversion radius). The observed 2-D images of the heat flow during the reconnection time exhibit a collection of pieces of many theoretical models.

The formation of a sharp point of the temperature perturbation at the low field side in the initial stage of the reconnection process appears to be consistent with the 'pressure finger' of the ballooning model accompanied with the temperature bulge; however, the fact that the observed reconnection event has no preferential location along the poloidal magnetic surface (observations at the low and high field sides) and the moderate value of the corresponding plasma beta are not compatible with this model [8, 9]. The time evolution of the hot spot/island during the reconnection process is inconsistent with that of the "quasi-interchange" model. Also, this is inconsistent with the model of "Y-point" formation at both separatrices of the island [16, 17]. In the "Y-point" reconnection process, the initial vertical extent of the magnetic field opening is expected to be much larger than the image of "X-point" reconnection. Observation of the finite extent of toroidal reconnection zone (1/3 of the toroidal circumference) is inconsistent with the full reconnection model where plasma pressure and current density can be removed on the characteristic reconnection time scale (τ_c) through a fully opened magnetic surface along the toroidal direction. The observed fact that the reconnection starts in a later stage of the precursor period suggests additional physical mechanisms that can delay the heat flow while reconnection is established or a different critical time based on different topology change of the magnetic reconnection process. The fact that heat flow from the core to the outside is highly collective suggests that the global stochasticity of field lines may not be the dominant mechanism for the removal of the heat in this case. The image of the "X-point" heat flow in the initial stage of a reconnection process initiated by a clear sharp temperature point accompanied with a strong kink or finite pressure effect on $m/n=1/1$ mode (swelling of the core temperature) and collective heat transfer behaviors of hot spot resembles the reconnection processes described by both the full reconnection and the ballooning model.

Advances in 2-D visualization diagnostic techniques provided new insights of the physics of the driven reconnection process (sawtooth oscillation) in the presence of strong guiding field. Improved theoretical modeling influenced by these findings will enhance the fundamental understanding of the magnetic reconnection mechanism which is beneficial for the control of future generations of magnetic confinement devices and may provide as well a better understanding of sawtooth phenomena in solar flares in which the guiding magnetic field is weak.

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FIGURE CAPTIONS

FIG. 1 2-D composite images of electron temperature fluctuations during the sawtooth crash phase are shown with the poloidal view of the plasma. (1) Partial image of the hot spot before reconnection corresponds to the peaked profile of electron temperature (2) Transient image taken in the middle of the reconnection process (3) Image after the reconnection is completed, corresponds to a flattened temperature profile. The schematic of core temperature profile changes as well as with the poloidal cross section of the toroidal plasma and the time history of the electron temperature at z=0 and R=187 cm are provided.

FIG. 2. 2-D images of the sawtooth crash at the low field side correspond to the times indicated in the electron temperature time trace at z=0 cm, R=191 cm. As the hot spot swells as shown in frames 3 and 4, a sharp temperature point is growing and crosses beyond the inversion radius. Eventually, the temperature point leads to the reconnection. Initially it forms an “X-point” in the poloidal plane (frame 5) and heat starts to flow to the outside through a small opening. The heat flow is highly collective and the opening is increasing up to ~15 cm. At the end, the heat is accumulated outside the inversion radius and the poloidal symmetry is recovered.

FIG. 3. 2-D images from the sawtooth crash at the high field side are shown with the time history of the electron temperature fluctuation at z=0, R=148 cm. The

reconnection process is quite similar to that at the low field side. A sharp temperature point develops with the moderate swelling of the hot core (frame 4), but fails to lead to reconnection in the first attempt. In the second attempt, the sharp temperature point accompanied with the strong swelling of hot spot (kink instability) (frame 6, 7) succeeds in crossing the inversion radius through a small opening (~a few cm). The opening increases up to ~10 cm and the heat flow is highly collective. The nested magnetic surfaces from the core push the heat flow out (frame 11) and eventually the symmetry is recovered (frame 12).

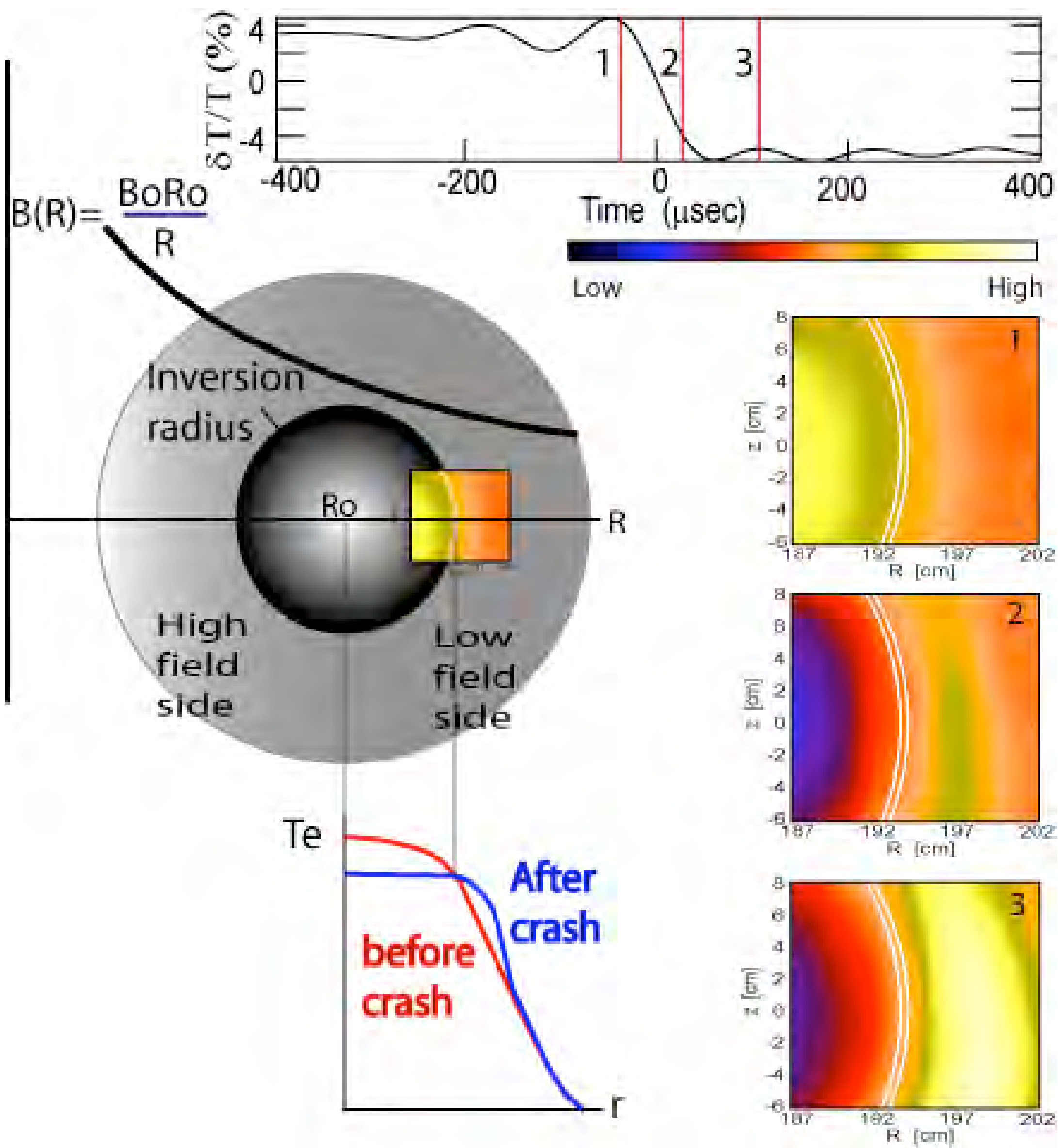


FIG. 1

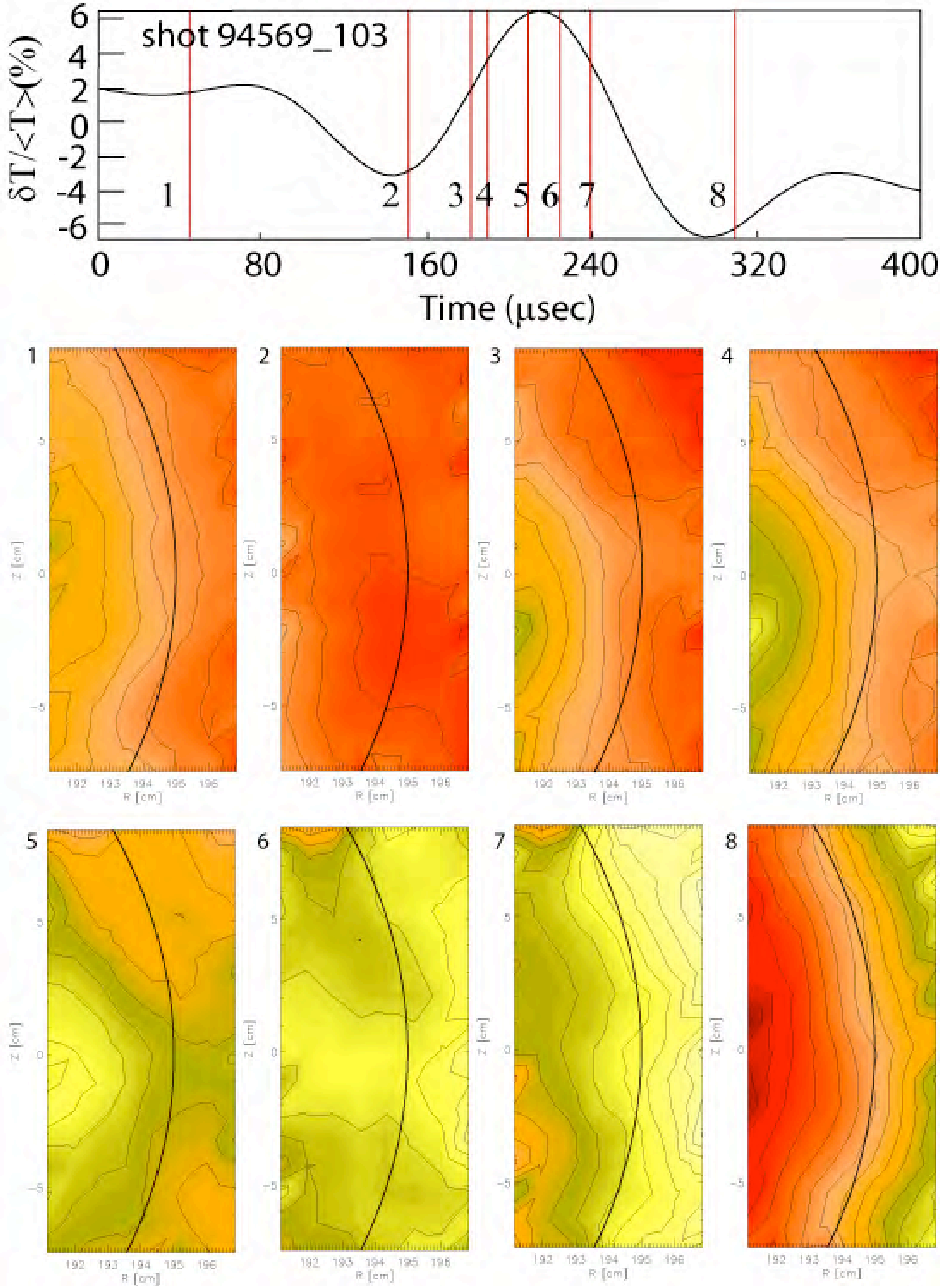
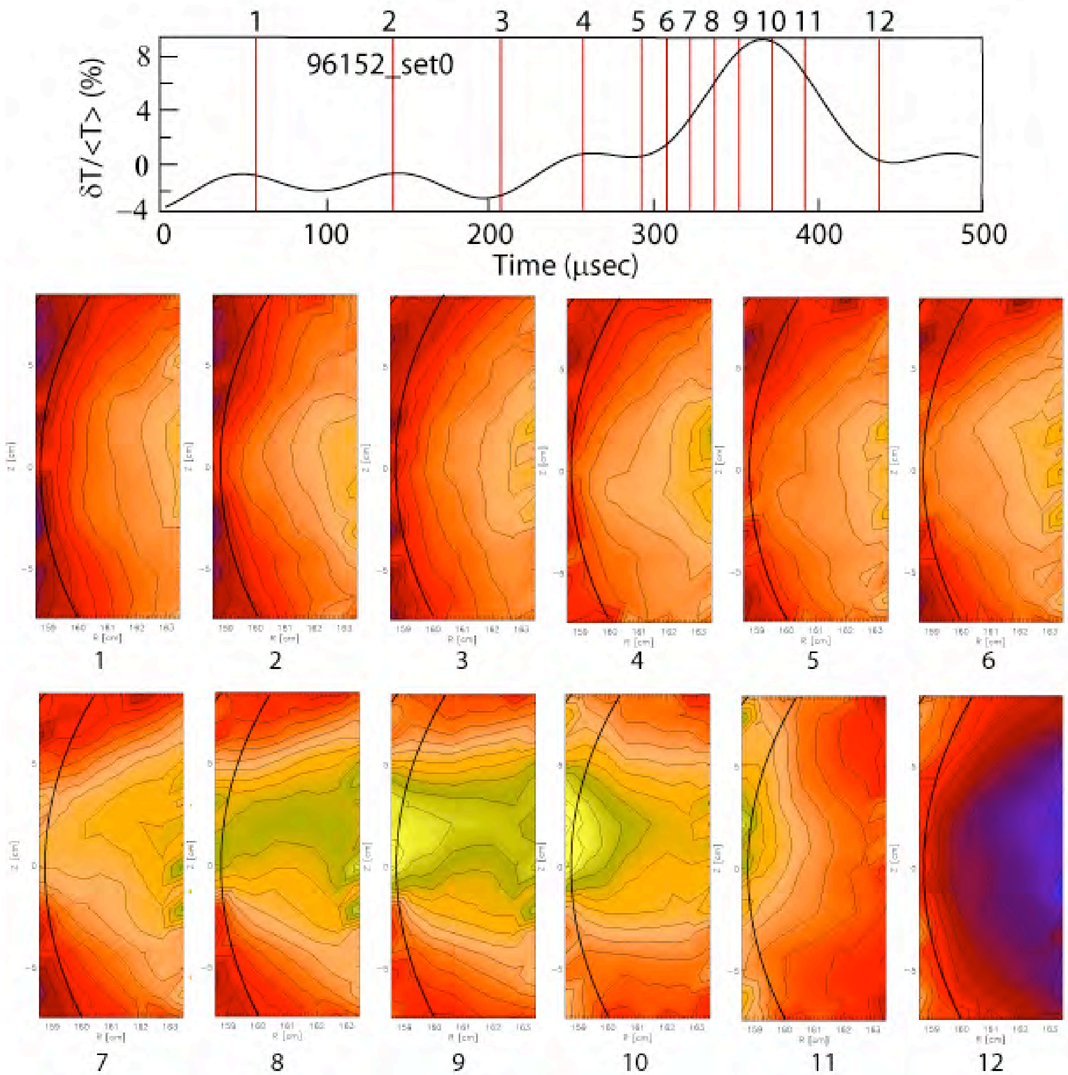


FIG. 2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Time (μsec)
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FIG. 3

External Distribution

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