Evolution of MHD Instabilities in Plasma Imploding Under Magnetic Field

D. Osin, E. Kroupp, A. Starobinets, G. Rosenzweig, D. Alumot, Y. Maron, A. Fisher, E. Yu, J. L. Giuliani, and C. Deeney

***Abstract*—Two-dimensional 3-ns-gated visible images, recorded at different times during the implosion of plasma under azimuthal magnetic field (Z-pinch), revealed ringlike instabilities followed by the development of axially and azimuthally nonuniform structures in the imploding plasma. Remarkably, the evolution in time of all structures was found to be highly repeatable in different shots, which should allow, through 3-D magnetohydrodynamics modeling, for systematically studying the development in time of these complex phenomena and correlating them with the initial plasma parameters. The data are also used to infer the time-dependent outer plasma radius and plasma radial velocities.**

***Index Terms*—Plasma implosion, visible imaging, Z-pinch.**

THE Z-PINCH implosions serve as intense sources of X-ray radiation that are of broad interest in the research toward inertial confinement fusion and the study of matter under high energy density [1]. In such systems, a cylindrical plasma column (typically formed out of an array of fine wires or a puff of gas) radially implodes under the azimuthal magnetic field resulting from axially driven high currents. In this process, acceleration-driven instabilities play a major role in the magnetohydrodynamics (MHD) of the plasma, including causing complex current paths in the plasma, magnetic-field penetration into certain parts of the plasma, and nonuniform disturbances in the implosion [2].

In this paper, a neon puff ($\sim$70 μg/cm) was imploded in 500 ns until stagnation on axis under a current pulse that rises to 500 kA [3]. The puff consists of a 38-mm-diameter outer shell and an $\sim$5-mm-diameter on-axis jet. The distance between the cylindrical nozzle (which serves as the cathode) and the cylindrical anode was 9.5 mm. Planar laser-induced fluorescence measurements on a similar system, but with an additional cylindrical nozzle, showed that the azimuthal uniformity of the initial gas density distribution is better than $\pm 15\%$ [4].

An f/16 optics with 7.5$\times$ demagnification and coupled to an intensified CCD, viewing the plasma in the radial direction, provided a submillimeter spatial resolution across the 38-mm-diameter plasma shell, together with a sufficient signal. The filter used transmitted visible light above 6000 Å ($T > 40\%$), thus mainly recording continuum radiation except for the earliest phase of the implosion where NeI–II line emission was significant too. The emission is thus nearly proportional to the square of the plasma density. The 3-ns-gated images were taken at different times along the implosion phase until the plasma stagnates on axis. Shown in Fig. 1 are 14 images of the imploding shell, most of them 50 ns apart, starting at $t = -500$ ns and ending at $t = 0$ (when the plasma stagnates on axis).

Surprisingly, it was found that the complex structures evolving in the plasma are repeatable in the different shots. Their repeatability even allows for tracking the growth of the structures at specific z-locations down to $t \cong -100$ ns.

The initial factors that govern the start of the growth of the nonuniform structures of the imploding shell are not known yet. One possibility is that they result from nonmonotonic variation of the initial gas density as a function of r and z, originating from the interaction between the gas jets as they propagate in the z-direction. The pictures also show the growth of the plasma portions that escape the implosion, pointing out the unresolved important question on the magnetic-field penetration into those portions. These pictures can serve as a unique tool for systematic examinations of 3-D MHD computations for the understanding of the initial conditions that give rise to the evolving structures and the time development of such structures.

These images are also used to plot the plasma visible-emitting radius as a function of time. It is seen that the radial motion of the plasma starts at $t = -250$ ns and ends at $t = 0$ with $r \sim 1$ mm. The radial velocities at the last 20 ns of the implosion are found to be $\sim 1.5 \times 10^7$ cm/s. This value is about 40% lower than the final implosion velocity obtained at $r < 0.5$ mm using X-ray imaging. This is expected since, in our experiments [3], [5], only $\cong$20% of the very leading edge of the imploding plasma constitutes the K-emitting portion of the stagnating plasma.

Manuscript received November 25, 2010; revised May 31, 2011; accepted May 31, 2011. Date of publication July 5, 2011; date of current version November 9, 2011. This work was supported in part by the Israel Science Foundation and in part by the DOE–Cornell University Excellence Center (USA).

D. Osin, E. Kroupp, A. Starobinets, G. Rosenzweig, D. Alumot, and Y. Maron are with the Weizmann Institute of Science, Rehovot 76100, Israel (e-mail: dima.osin@gmail.com; eyal.kroupp@weizmann.ac.il; alexander.starobinets@weizmann.ac.il; Guy.rosenzweig@weizmann.ac.il; Dror.alumot@weizmann.ac.il; Yitzhak.Maron@weizmann.ac.il).

A. Fisher is with the Faculty of Physics, Technion–Israeli Institute of Technology, Haifa 32000, Israel (e-mail: amnon.fisher@gmail.com).

E. Yu is with the Sandia National Laboratories, Albuquerque, NM 87185-1194 USA (e-mail: epyu@sandia.gov).

J. L. Giuliani is with the Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375 USA (e-mail: john.giuliani@nrl.navy.mil).

C. Deeney is with the Department of Energy, Washington, DC 20585 USA (e-mail: chris.deeney@nnsa.doe.gov).

Digital Object Identifier 10.1109/TPS.2011.2159019

0093-3813/$26.00 © 2011 IEEE

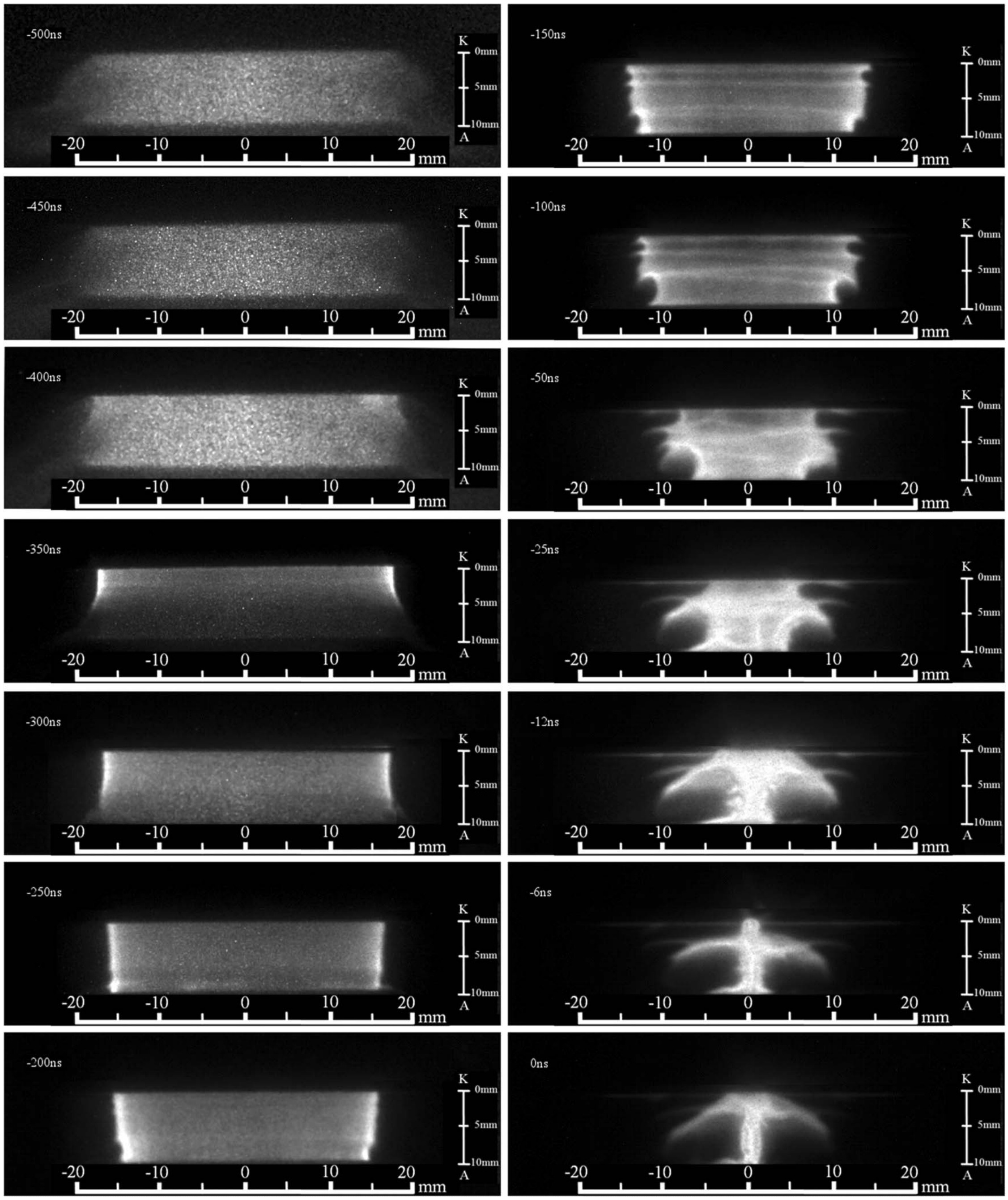

Fig. 1. Fourteen successive 2-D 3-ns-gated visible images of the imploding plasma under azimuthal magnetic field recorded at different times along the implosion phase. The times (where $t = 0$ is the pinch time) are indicated on the upper left corner of each image. The intensity of each image is normalized to the peak intensity of that frame.

REFERENCES

[1] M. K. Matzen, M. A. Sweeney, R. G. Adams, J. R. Asay, J. E. Bailey, G. R. Bennett, D. E. Bliss, D. D. Bloomquist, T. A. Brunner, R. B. Campbell, G. A. Chandler, C. A. Coverdale, M. E. Cuneo, J.-P. Davis, C. Deeney, M. P. Desjarlais, G. L. Donovan, C. J. Garasi, T. A. Haill, C. A. Hall, D. L. Hanson, M. J. Hurst, B. Jones, M. D. Knudson, R. J. Leeper, R. W. Lemke, M. G. Mazarakis, D. H. McDaniel, T. A. Mehlhorn, T. J. Nash, C. L. Olson, J. L. Porter, P. K. Rambo, S. E. Rosenthal, G. A. Rochau, L. E. Ruggles, C. L. Ruiz, T. W. L. Sanford, J. F. Seamen, D. B. Sinars, S. A. Slutz, I. C. Smith, K. W. Struve, W. A. Stygar, R. A. Vesey, E. A. Weinbrecht, D. F. Wenger, and E. P. Yu, "Pulsed-power-driven high energy density physics and inertial confinement fusion research," *Phys. Plasmas*, vol. 12, no. 5, pp. 055503-1–055503-16, May 2005.

[2] D. D. Ryutov, M. S. Derzon, and M. K. Matzen, "The physics of fast Z pinches," *Rev. Mod. Phys.*, vol. 72, no. 1, pp. 167–223, Jan. 2000.

[3] D. Osin, "Ion dynamics in hot and dense plasmas under intense magnetic fields," Ph.D. dissertation, Weizmann Inst. Sci., Rehovot, Israel, 2008.

[4] G. Rosenzweig, "Determining the density distribution of a gas injected through a multi-nozzle system for plasma implosion experiments," M.S. thesis, Weizmann Institute of Science, Rehovot, Israel, 2007.

[5] E. Kroupp, D. Osin, A. Starobinets, V. Fisher, V. Bernshtam, Y. Maron, I. Uschmann, E. Förster, A. Fisher, and C. Deeney, "Ion-kinetic-energy measurements and energy balance in a Z-pinch plasma at stagnation," *Phys. Rev. Lett.*, vol. 98, no. 11, p. 115001, Mar. 2007.