Shock waves in a Z-pinch and the formation of high energy density plasma

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Shock waves in a Z-pinch and the formation of high energy density plasma


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A Z-pinch liner, imploding onto a target plasma, evolves in a step-wise manner, producing a stable, magneto-inertial, high-energy-density plasma compression. The typical configuration is a cylindrical, high-atomic-number liner imploding onto a low-atomic-number target. The parameters for a terawatt-class machine (e.g., Zebra at the University of Nevada, Reno, Nevada Terawatt Facility) have been simulated. The 2-1/2 D MHD code, MACH2, was used to study this configuration. The requirements are for an initial radius of a few mm for stable implosion; the material densities properly distributed, so that the target is effectively heated initially by shock heating and finally by adiabatic compression; and the liner’s thickness adjusted to promote radial current transport and subsequent current amplification in the target. Since the shock velocity is smaller in the liner, than in the target, a stable-shock forms at the interface, allowing the central load to accelerate magnetically and inertially, producing a magneto-inertial implosion and high-energy density plasma. Comparing the implosion dynamics of a low-Z target with those of a high-Z target demonstrates the role of shock waves in terms of compression and heating. In the case of a high-Z target, the shock wave does not play a significant heating role. The shock waves carry current and transport the magnetic field, producing a high density on-axis, at relatively low temperature. Whereas, in the case of a low-Z target, the fast moving shock wave preheats the target during the initial implosion phase, and the later adiabatic compression further heats the target to very high energy density. As a result, the compression ratio required for heating the low-Z plasma to very high energy densities is greatly reduced. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4769264]

I. INTRODUCTION

The Z-pinch is a simple, pulsed-power-driven, plasma-compression system, in which the azimuthal-magnetic field of a cylindrical-plasma discharge compresses the plasma by a self-generated force. At maximum compression, the Z-pinch produces an intense burst of particles, X-rays, and neutrons, if deuterium and tritium are used. Over the past five decades, the study of Z pinches has continued and remains an active area of research, for the study of atomic-physics, controlled-thermonuclear fusion, nuclear-effects simulation, and stockpile stewardship.

Z-pinches are susceptible to a variety of instabilities that limit their ability to attain extreme-energy density. The most common are the m = 0, 1 MHD instabilities, and the Rayleigh-Taylor (RT) instability. The RT instability has the fastest growth rate. For impulsively accelerated, mixed-material, liner-on-target pinches, i.e., those of present interest, the Richtmyer-Meshkov (RM) instability may also be important. Many experimental configurations have been used to mitigate the effects of acceleration-driven RT instabilities, for example: distributing the load mass quasi-uniformly (as in a large-array of fine wires) using a gas-puff to disperse uniformly the mass distribution, ensuring a high-degree of initial plasma pre-ionization, imposing a sheared-plasma flow, pre-magnetizing the pinch with an axial-magnetic field, nestling the pinch as a series of concentric loads, to effectuate a staged-energy transfer etc.

The specific approach studied here involves staging. Typically a thin, cylindrical, high-Z liner implodes onto a low-Z target, as illustrated in Figure 1. Experiments performed on a microsecond-implosion-time, mega-ampere system, provide evidence that staging occurs. Modeling indicates that a similar configuration deployed on a 100 ns, terawatt (TW) system, could provide a magnetically accelerated, inertially confined, high-energy-density pinch.

The following key features characterize a staged Z-pinch implosion. As the liner implodes, a shock front is formed that detaches from the slower-moving liner plasma. The shock collides with the outer surface of the low-mass, target plasma, accelerating it inward. The shock is partially transmitted and reflected at the interface. The shock speed in the low-Z target plasma is much larger than it is in the high-Z liner plasma, thus the shock transit time in the target is...
short and the plasma is rapidly heated. Adiabatic compression and current amplification follow as the bulk of the liner mass converges to the axis. The heating of a cylindrical plasma by adiabatic compression can be approximated by

$$T_f = T_0 \left( \frac{r_0}{r_f} \right)^{2(\gamma - 1)},$$

where $T_f$ is the final plasma temperature, $T_0$ is the initial plasma temperature, $r_0$ is the initial plasma radius, $r_f$ is the final plasma radius, and $\gamma$ is the adiabatic index. If adiabatic compression alone is used, a compression ratio of 300 would be required to achieve a final temperature of 10 keV from an initial temperature of 5 eV. The additional pre-heating caused by the shock waves in the low-Z target plasma to 100 eV reduces the required compression ratio to 30 to achieve the same 10 keV final temperature.

Shocks may accelerate surfaces to high speeds, without instability.\textsuperscript{31–33} Thus, for a matched implosion system, shock compression of a target may provide a direct method for accessing faster implosion times and high-energy-density states. By iterating through parameter scans of liner and target initial densities, initial temperatures and initial radii, among others, we have delayed the onset of instabilities, while accumulating high-energy in a target plasma.

In recent years, our efforts have been focused on staged Z-pinch implosions for multi-terawatt, multi-MJ generators, for the production of fusion energy. Timing and optimization of the dynamical processes outlined above is critical for producing a high-energy-density plasma, for example: the current-pulse rise time and its amplitude; the initial radius, atomic number, thickness, and mass of the liner; the initial radius, thickness, and mass of the target; shock pre-heat of the target; the level of current diffusion, and its subsequent amplification by flux-compression; the magnitude of the compressed magnetic field that confines x-particles, which heat the target; radiation transport; and other effects.\textsuperscript{34,35} In these studies, it seems obvious that shock waves play a critical role in the coupling of the electrical energy to thermal energy of the plasma.

Shock waves often arise in nature because of a balance between wave-breaking nonlinear and wave-damping dissipative forces.\textsuperscript{36} Collisional and collisionless shock waves can appear in ion acoustic wave propagation because of friction between the particles and wave-particle interactions,\textsuperscript{37,38} respectively. In magnetized plasmas, the other natural mode of interest could be the magnetoacoustic waves which propagate perpendicular to the magnetic field lines of force and can form magnetoacoustic shock waves.\textsuperscript{39}

In this paper, we present computer simulation studies of the formation of magnetoacoustic shock waves and their role in heating plasmas that are relevant for magneto-inertial fusion schemes and for astrophysical environments. Our results reveal that magnetoacoustic shock waves can only appear once the magnetic field diffuses into the plasma. In the case with Ag liner-Ag target, magnetic field diffuses all the way to the axis, thus the dominant shock waves could be of magnetoacoustic in nature. Furthermore, for Ag liner-H target, the dominant mode in Ag plasma is still magnetoacoustic but in H plasma, only ion acoustic waves play a dominant role until the temperature rises significantly and the Mach number becomes smaller than unity. The compression of a hydrogen plasma is then adiabatic in nature. Thus, the combination of shock heating and adiabatic compression heating plays the role of producing high energy density plasma. Although the compression of target is adiabatic towards the end, it is still compressed by a shock front produced at the interface by a dense Ag plasma, which is inherently stable. In this way, the shock waves play a crucial role in creating a high energy density plasma.

II. MHD SIMULATION

Our simulations consider the implosion dynamics of a thin cylindrical liner plasma compressing a target plasma column. They were carried out using the two and one-half dimensional ($2\frac{1}{2}$)-D MHD code MACH2.\textsuperscript{40,41} A $2\frac{1}{2}$-D code has a two-dimensional grid, but carries all three components of the velocity and magnetic field. MACH2 is a time-dependent arbitrary Lagrangian Eulerian (ALE) simulation code that solves the resistive MHD continuity, momentum, energy, and magnetic field equations on a computational grid composed of quadrilateral cells. The code uses finite volume differing. It is a single-fluid three-temperature code that uses either analytic models or tabular values (SESAME tables at Los Alamos National Laboratory) (http://t1web.lanl.gov/newweb_dir/t1sesame.html) for the state and transport variables. In modeling the dynamics, the plasma is assumed to be optically thin. This radiation model works quite well during the implosion phase, but is not expected to give quantitative results for the radiation pulse at the peak implosion when plasma density is comparable to solid density. The liner plasma used the SESAME tables for the state and transport variables. The target plasma used the SESAME tables for the state variables and a Spitzer analytical model for the transport variables. The Zebra generator\textsuperscript{42} was modeled with a single-loop equivalent to a R-L circuit driven by the measured voltage waveform, as shown in Fig. 2. For these simulations, the series resistance was 1.9 Ohm and the inductance 69 nH. Figure 3 displays the corresponding current waveform obtained from a typical Mach2 simulation run, which is quite similar to the experimentally obtained waveform.
For this study, we chose to use the full \((2_{1/2})\)-D capability of MACH2. Even though MACH2 can be used in a quasi 1-D mode, it is not truly one dimensional. The one dimensional approximation is generated by forcing MACH2 to consider only one cell in the axial direction but multiple cells in the radial direction for this z-pinch configuration. This is not much of a problem numerically when the adaptive Eulerian mode is used. When purely Lagrangian mode is used, however, the four points defining the corners of each cell can develop different velocities and thus “tangle.” This illustrates the fact that the simulation is not truly one dimensional. Point centered fluid velocities differ at each corner of each cell. So, although the two dimensional simulation has the appearance of a one dimensional simulation, axial fluid velocities are not zero. Comparing 1-D and 2-D simulations of this configuration show minor differences in a number of results such as peak implosion times and peak final temperatures. The essential physics remains unchanged. We, therefore, believe it is most appropriate to use a two dimensional approach to simulate this configuration.

We focused here on two cases where a thin silver liner of 6 mm diameter implores onto a low density solid fill plasma of silver or hydrogen. The simulations were run with 3 computational regions. All three regions extend the full length of the plasma in the axial direction (0.0 to 4.0 cm). The first region extends from the axis to 0.1 mm in the radial direction. The second region extends from 0.1 mm to 2.9 mm and the third from 2.9 mm to 3.0 mm. All three regions were descritized into 96 zones axially. The first and second regions were descritized into 64 zones each radially, and the third region was descritized into 32 zones radially. Increasing the descritization in the axial or radial directions did not significantly alter the results. Thus, this level of descritization was considered adequate for resolving the shock waves that developed. The simulation was run in Eulerian mode axially and in ALE mode radially. This was done to prevent the computational grid from curling back on itself. The SESAME equation of state table was used for simulating the silver equation of state and transport parameters. The SESAME tables were also used for the hydrogen simulation except for the conductivity, in which a Spitzer analytical model was used.

Initial parameters used in our simulations and the peak values obtained after the implosion are summarized in Table I. In order to investigate the dynamics beyond peak implosion a low level density perturbation of 0.1% is imposed throughout the simulation region.

Figures 4 and 5 display the temporal evolution of the ion number density and the ion temperature versus radius, respectively, for 2-D calculation with 0.3-cm initial radius (c.f. Table I) at 100, 120, and 140 ns. As the implosion proceeds, the shock waves propagate radially inwards first through the liner plasma and then through the fill plasma. A layer of plasma peals off from the inner surface of the liner,
which builds over time and compresses the low density plasma fill. In Figure 4, where both the liner plasma and fill plasma are made from silver, these layers propagate all the way and collapse on the axis. A reflected shock wave from the axis propagates backward and by 140 ns, a dense plasma column forms on the axis, but temperature of 8–10 eV remains uniform across the radius. In Figure 5, where the liner plasma is made of silver and the fill plasma is made of hydrogen, the peeled off layer due to shocks stagnates at the interface with a sharp boundary. The right-side panel of temperatures in Fig. 5 shows a distinct difference between the two plasmas. The temperature of liner plasma remains 8–10 eV, whereas the temperature of hydrogen fill plasma exceeds 100 eV by 140 ns. This rise of the temperature is mainly due to the shock
heating and compression by the peeled off layer. At 140 ns, we see the sign of instability at the shock interface that may be attributed to the RM instability.\textsuperscript{12,13}

In order to further understand the role of shock waves, the plasma $\beta$, which is the ratio between the plasma and magnetic field pressures, is plotted as a function of radius in Fig. 6 at 120 ns. Figure 6(a) shows the line-outs of Ag-Ag, whereas Fig. 6(b) shows for the Ag-H load implosion. Figure 6(a) exhibits the plasma $\beta \approx 1$ throughout the radius for Ag on Ag target except on the axis, where $\beta \gg 1$. On the other hand, for Ag-H again $\beta \approx 1$ in the region of Ag plasma, but in the region of H plasma $\beta \gg 1$. The boundary of liner and target plasmas is separated by a sharp discontinuity that builds up in time, due to the stagnation of shock waves.

Figure 7(a) displays the radial velocity at 120 ns and Fig. 7(b) displays Alfvén and ion sound speeds versus radius again at 120 ns. At this point of time, for Ag-H the outer liner silver plasma extends from 0.13–0.26 cm filled with target hydrogen plasma. In the liner plasma region, the radial flow

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Ion density and temperature for silver liner imploding on hydrogen fill plasma at 100 ns, 120 ns, and 140 ns.}
\end{figure}
velocity is negative, which means that the plasma flow is radially inward, whereas in the target plasma, the radial flow velocity is positive, which means that the flow is radially outward. This happens when the shock waves propagating inward reflect back from the pinch axis and collide at the interface with the incoming shock waves. In the liner plasma region, the radial flow velocity is larger than both the Alfvén and ion sound speeds, thus generating a shock wave of magnetosonic nature. Inside the target plasma, the radial velocity is larger than Alfvén speed, but much less than ion sound speed. Thus, a weaker reflected shock wave propagates radially outward, which is also evident from the Mach number plot of Figure 7(c). Figure 7(c) displays the magnetosonic Mach number \( M_m \). Again, on the left-side are plots for Ag-Ag, whereas on the right-side are the plots for Ag-H. Note the high Mach number computed for this pinch, illustrating the importance of considering shocks in both producing a stable-dynamic compression/acceleration and providing energy transfer to the load. The magnetosonic Mach number for these simulations is calculated at each point in the computational grid using the following equation:

\[
M_m = \sqrt{v_r^2 + (v_\theta^2 + v_z^2)/C_s^2 + v_A^2},
\]

where \( v \) is the flow velocity, \( C_s = \sqrt{\gamma p/h} \) is the sound speed, and \( v_A = B/\sqrt{(\mu_0 \rho)} \) is the Alfvén speed.

Shock waves transport mass, current, and magnetic field and propagate radially during the pinch implosion. In silver plasma, we have \( M_m \approx 3.4 \), whereas in hydrogen plasma, \( M_m < 1 \). At the interface, which is at \( r = 0.13 \) cm, a sharp discontinuity develops and the magnetosonic Mach number drops to the lowest value. Both Alfvén and sound speeds achieve a much larger value than the radial flow velocity at the interface of Ag and H plasma. At 120 ns, the Alfvén speed drops rapidly in magnitude, but the ion sound speed remains the same over the entire region of hydrogen plasma. By 120 ns, an azimuthal magnetic field of 140 kG develops at the interface in comparison with 730 kG on the outer surface. The inner peak at 0.14 cm also signifies the flux compression at the interface of H and Ag plasma. At 140 ns, it reaches up to 0.2 MG, which is almost 20% of the outer magnetic field of 1.0 MG. Such strong magnetic field diffusion and compression results in enormous value of 58 MG at peak implosion time, as seen in Fig. 10(d).

Figure 9 displays the time evolution of an azimuthal magnetic field versus radius at 100, 120, and 140 ns. The left-side panel shows a strong diffusion of the magnetic field in Ag-Ag implosion all the way to the axis, which cannot be attributed to classical diffusion time and may be attributed only to the propagation of discontinuity produced by shock waves. For the case of Ag-H, strong diffusion of magnetic fields is seen in Ag plasma, but weak diffusion in the hydrogen plasma. By 120 ns, an azimuthal magnetic field of 140 kG develops at the interface in comparison with 730 kG on the outer surface. The inner peak at 0.14 cm also signifies the flux compression at the interface of H and Ag plasma. At 140 ns, it reaches up to 0.2 MG, which is almost 20% of the outer magnetic field of 1.0 MG. Such strong magnetic field diffusion and compression results in enormous value of 58 MG at peak implosion time, as seen in Fig. 10(d).

Figures 10 and 11 display the results for Ag-Ag and Ag-H near the peak implosion time of 167.4 ns. These results are for the same 2-D calculation with a 0.3-cm initial radius (c.f. Table I). In both these figures on the left-side are the 2-D
results and 1-D “line-outs” for the ion number density, the ion temperature, the axial current density, and the azimuthal magnetic field for Ag liner implosion over Ag target plasma. On the right-side are the same for Ag liner implosion over H target plasma. 2-D iso-contour for both cases shows that 0.3-cm initial radius produces a stable pinch at peak compression. For Ag-Ag at the peak implosion, a dense low temperature core of $4 \times 10^{23}/\text{cm}^3$ is formed, which is surrounded by lower density ($25-30 \text{ eV}$ plasma and a magnetic field of 34 MG falling to 5 MG. For Ag-H at the peak implosion, the density of hydrogen plasma reaches $1.0 \times 10^{22} \text{ cm}^{-3}$ with a temperature of 10 keV; equivalent to 16 MJ/cm$^3$. This high energy-density hydrogen plasma is surrounded by a thin and dense layer of Ag plasma of $2.8 \times 10^{23} \text{ cm}^{-3}$ with a temperature of 50 eV. This layer is surrounded by a sharp lower density plasma of $\approx 10^{20}/\text{cm}^3$ extending up to 0.01 cm. The
azimuthal magnetic field outside the hydrogen plasma is $B_{\theta} \sim 58$ MG. In both cases, current reversal develops between the inner layer and the outer layer, and the enhanced magnetic field is due to the flux compression as proposed earlier. The current loop that develops is much larger in size for Ag-H as compared to Ag-Ag, as seen in Figure 10(c). This is due to the fact that cold silver plasma is much more diffusive as compared to super hot hydrogen plasma. The sign of Raleigh-Taylor instability can be seen on the outer surface of the liner plasma, whereas the target plasma remains stable up until the peak implosion. Once the pinch start expanding outward, this surface becomes unstable too.

### III. DISCUSSION

In this paper, we have found that the Ag liner plasma expands in the much lower pressure H plasma, acts as a piston upon it, and launches a perturbation (likely a shock) in the H plasma (which is first seen at about 29 ns in ion pressure $p_i$ and 43 ns in ion density $n_i$). The shock propagates to
the axis where it is reflected. The average propagation speed during the round trip is \( v \approx 8.6 \times 10^6 \text{ cm/s} \). During this time, the temperature of the undisturbed H plasma increases from 5 to 15 eV. The corresponding sound speed ranges from \( C_s \approx 2.8 \times 10^6 \text{ cm/s} \) to \( 4.9 \times 10^6 \text{ cm/s} \), giving a sonic Mach number \( M_s \approx 2 \). The shocked plasma is heated up to 25 to 30 eV. For the same time interval, the Alfvén speed is \( V_{A,max} > 3.3 \times 10^6 \text{ cm/s} \) (for the maximum value of the magnetic flux density in the propagation range), so \( M_A < 2.6 \). As the lower limit of the ion number density cannot be discerned in the plots, it is possible that \( M_A \leq 1 \).

The shock is reflected again at the piston, and the process repeats as the piston is accelerated toward the axis. As more energy becomes available to the system in time, the ion density, temperature, and the magnetic field in the H plasma increase. The perturbation velocity also increases. For example, for the time interval 122.7 to 132.6 ns (when the perturbation propagates away from the piston to the axis and is reflected back to the piston), the Mach numbers are \( M_s \approx 1.5 - 1.8 \) and \( M_A \approx 9 - 14 \). The magnetosonic Mach number is \( M_m \approx 1.4 - 1.8 \). The accuracy of these estimates is illustrated by applying the same technique to the interval

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**FIG. 9.** Azimuthal magnetic field versus radius \( r \) for silver liner on silver fill plasma (left side panels) and silver liner on hydrogen fill plasma (right side panels) at 100 ns, 120 ns, and 140 ns.
128.4 ns to 138.3 ns (when the perturbation bounces from the axis) is reflected at the piston and propagates back to the axis. Taking the undisturbed plasma temperature, one obtains $M_s \approx 1.1 - 1.3$. For the maximum magnetic field and the minimum density in the propagation range, the Alfvén and magnetosonic Mach numbers are $M_A \approx 1.4 - 1.5$ and $M_m \approx 0.8 - 1$, respectively. Above, the propagation speeds of the perturbation are estimated by dividing the total propagation distance between two reflections on the same boundary (the piston or the axis) to the propagation time.

FIG. 10. Contours of plasma parameters at peak implosion time, (a) ion number density, (b) ion temperature, (c) axial current density, and (d) azimuthal magnetic field for silver liner imploding on silver fill plasma (left panels) and silver liner on hydrogen fill plasma (right panels).
These average values are: $8.6 \times 10^6 \text{ cm/s (43 to 93 ns)}$, $1.7 \times 10^7 \text{ cm/s (122.7 to 132.6 ns)}$, and $1.4 \times 10^7 \text{ cm/s (128.4 to 138.3 ns)}$. All are higher than the radial velocity shown in Figure 7. At 122.7 ns, the closest time to that of Fig. 7 at which the parameters are estimated here, $C_s \approx 9.8 \times 10^6 \text{ cm/s}$ and $V_A \approx 1.2 \times 10^6 \text{ cm/s}$. Magnetic field diffuses in the H plasma and remains trapped in there when the temperature and, therefore, the local conductivity at the Ag-H interface increases. The magnetic field appears to be frozen in the H plasma early on (30 to 40 ns), when the diffusion time is sub-nanosecond. This is indicated by a low amplitude perturbation in B that propagates in phase with the perturbations in the ion number density and the ion temperature. A tangential discontinuity seems to form at the Ag-H interface. The temperature

![Mid-plane "line-outs" at peak implosion time of (a) ion number density, (b) ion temperature, (c) axial current, and (d) azimuthal magnetic field for silver liner imploding on silver fill plasma (left panels) and silver liner on hydrogen fill plasma (right panels).](image)

FIG. 11. Mid-plane "line-outs" at peak implosion time of (a) ion number density, (b) ion temperature, (c) axial current, and (d) azimuthal magnetic field for silver liner imploding on silver fill plasma (left panels) and silver liner on hydrogen fill plasma (right panels).
increases in the region where the Ag liner plasma interacts with the H plasma and the local magnetic field is compressed. For plasma parameters \(n_i, T_i, B\) measured at 120 ns on both sides of the discontinuity

\[
\begin{align*}
\text{Ag:} & \quad 2 \times 10^{18} \, \text{cm}^{-3}, \ 4 \, \text{eV}, \ 7 \times 10^4 \, \text{G}, \\
\text{H:} & \quad 3 \times 10^{18} \, \text{cm}^{-3}, \ 60 \, \text{eV}, \ 7 \times 10^4 \, \text{G},
\end{align*}
\]

the diffusion time through 0.01 cm is 0.1 ns for Ag\(^{+1}\) ions and 5.8 ns for H\(^{+}\), and the ion Larmor radius is 0.7 cm (directed) for Ag\(^{+1}\) and 0.01 cm (thermal) for H\(^{+}\) ions. These values indicate that the magnetic field is insufficient for preventing the Ag ions from mixing into the H plasma and thus increasing the radiative losses. Furthermore, these values are not consistent with the magnetic field structure in the Ag plasma. For these values of the plasma parameters, the derived quantities \(\left(V_A, C_s\right)\) are

\[
\begin{align*}
\text{Ag:} & \quad 1 \times 10^6 \, \text{cm/s}, \ 2.5 \times 10^5 \, \text{cm/s}, \ \text{(for } Z = 1) \\
\text{H:} & \quad 9 \times 10^6 \, \text{cm/s}, \ 1 \times 10^7 \, \text{cm/s},
\end{align*}
\]

and compare reasonably well with those plotted in Fig. 7.

IV. CONCLUSION

In this paper, we have presented a novel mechanism for producing high energy density plasma with a modest compression ratio of 30 for a terawatt Z-pinch machine by 2D simulations using the state-of-the-art MACH2 code. A compression ratio of 30 to 40 has been achieved routinely in various Z-pinch facilities, however this level of compression ratio alone cannot heat the plasma to KeV range uniformly. The kind of staging described above where a high Z-liner plasma compresses a low Z-target plasma may lead to a significantly high temperature even with this level of modest compression ratio. The formation and study of such plasma are of great interest for thermonuclear fusion, X-ray laser, and many other laboratory applications. It may also help to understand many salient features of astrophysical plasmas in nature. Role of shock waves is identified to play a crucial role in the dynamics, energy coupling, and the formation of a stable high energy density uniform plasma of up to 16 MJ/cm\(^3\). The shock waves are predominantly magnetosonic in nature and can transport currents and magnetic fields across the radial profile much faster than the classical diffusion time scales. The role of shock waves becomes significant when a dense high-Z liner plasma implodes on a low density hydrogen target plasma. The propagation of shock waves in the liner plasma stagnates their energy at the interface of liner and target plasmas, which creates a separate stable implosion of the target plasma leading to a high-energy density plasma. As the implosion proceeds, the current builds up in this peeled off layer, which develops due to shock stagnation and the azimuthal magnetic flux keeps compressing, reaching to large values above 50 MG at the peak implosion. In the case of deuteron and tritium target, the charged particles produced in the thermonuclear fusion reaction can easily be trapped by this isolating magnetic field and deposit their energy into the target plasma. This may lead to ignition in a reasonable size pulsed power machine, which is operational in various laboratories around the globe.

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