Generation of sub-Mbar pressure by converging shock waves produced by the underwater electrical explosion of a wire array

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(Received 8 February 2006; published 26 May 2006)

We report a demonstration of a generation of sub-Mbar pressure on the axis of the implosion wave produced by an underwater electrical explosion of a cylindrical wire array. The array was exploded by microsecond time scale discharge of a capacitor bank having a stored energy of 4.5 kJ and discharge current amplitude of up to 90 kA. Optical diagnostics were used to determine the time of flight and the trajectory of the converging shock wave. This data were applied for a calculation of the water flow parameters using one-dimensional (1D) and 2D hydrodynamic calculations and the Whitham method. All three methods have shown that the shock wave pressure at 0.1 mm from the axis reaches 200 kbar.

DOI: 10.1103/PhysRevE.73.057301 PACS number(s): 47.40.−x, 52.80.Qj

The generation of an ultrahigh pressure is one of the key issues in research related to high energy physics. The most advanced methods used to obtain ultrahigh pressure are *Z*-pinch, laser irradiation of a target and chemical explosion [1]. Using these methods, extremely high pressures of ≥ 10 Mbar were achieved with initially stored energy of ≥ 1 MJ. *Z* pinch employs a cumulation principle by transferring the magnetic energy of the current in the electromagnetically exploding liner to the kinetic energy of the particles on the axis of the implosion. Direct cumulation of the energy of the shock waves (SWs) is also possible by creating cylindrical or spherical converging SWs [2–4] by explosives detonation methods. In the experiments [5], in the focus of the spherically imploding detonation waves propagating in a stoichiometric propane-oxygen mixture in a detonation chamber an ion temperature of about 10^8 K was observed. Experiments on electromagnetically driven cylindrical SW implosion in water have been reported [6]. In these experiments a 23 MJ capacitor *Z*-pinch facility was used to accelerate and implode electromagnetically the cylindrical metal liner or shell onto a coaxial and concentrically located thin target containing water. All of these experiments were carried out in a time scale of $\geq 10^{-5}$ s. Within this time scale numerous experiments of underwater electrical wire explosions (UEWE) showed that the process of wire explosion is accompanied by the generation of SW, with pressures up to 30 kbar. Also, it was shown that the efficiency of the transfer of the stored energy to the SW is $\leq 40\%$ [7]. In the case of nanosecond time scale UEWE, scaling laws show that a larger pressure can be achieved due to the increase in the rate the energy deposition [8].

In this paper we present results of experiments and hydrodynamic calculations which show that even microsecond time scales underwater electrical explosion of a cylindrical wire array using a generator with stored energy of several kJ can be considered as a promising method for a generation of sub-Mbar pressures with initial stored energy of only several kJ employing energy cumulation by the cylindrical SW implosion in water. In order to achieve the matching between a pulsed power generator and the imploding load, i.e., to deliver all the stored energy to the load during the first quarter of the discharge period, a cylindrical array of thin Cu wires in the form of a zigzag was used. This load design allows us to decrease the inductance of the load and to increase the effective length of the wire keeping the load volume small, at a few cm^3, i.e., to achieve high energy density deposition, similar to MJ experiments [6].

An aperiodical discharge of four Maxwell type capacitors connected in parallel with total capacitance of ≈ 10 μF and stored energy of 4.5 kJ at a charging voltage of 30 kV [9] was used for the electrical explosion of a Cu wire array. The array was placed inside an experimental chamber filled with technical water and having windows for optical access and high voltage input. The wire array used consisted of four Cu wires each 0.2 mm in diameter and 70 mm in length, con-

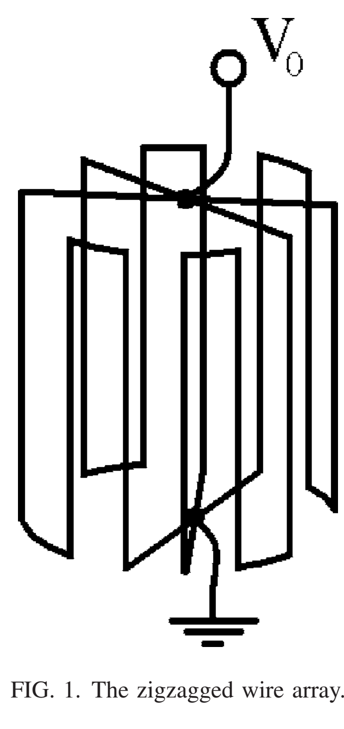

FIG. 1. The zigzagged wire array.

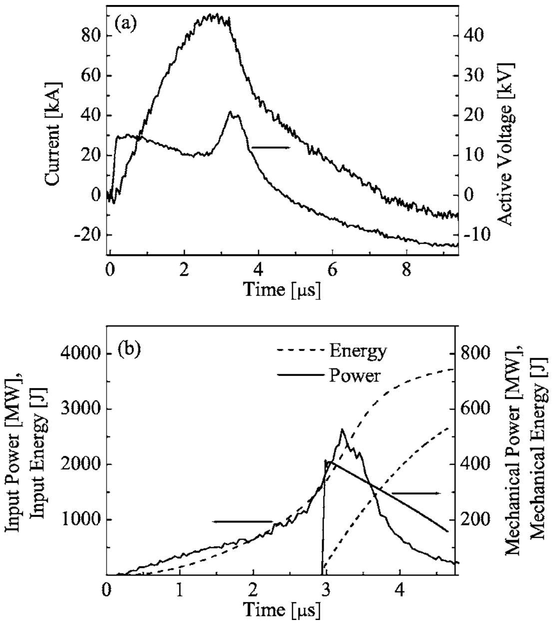

FIG. 2. Typical wave forms of (a) discharge current, active voltage; (b) dissipated power and absorbed energy and mechanical power and work.

nected in parallel. Each wire makes three zigzags (see in Fig. 1) resulting in a total of 12 wires. The Cu wires were placed on an inner surface of a perplex cylinder 20 mm in height and either 10 or 20 mm in inner diameter (i.d.). The azimuthal separation of wires was 3 and 1.5 mm for the cases of cylinders of 20 mm i.d. and 10 mm i.d., respectively.

A Pierson current transformer and two Tektronix voltage dividers were used to measure the discharge current I_d and voltage drop ΔV, respectively on the exploding wire array. The inductive voltage $L_{ar} dI_d/dt$, where L_{ar} is the array inductance, has been subtracted from the measured value of ΔV to obtain the resistive component of the voltage ΔV_{res} on the wire array. A shadow image of the generated SW was recorded by a streak EOK-XX camera and framing camera 4Quick04A (frame duration of 30 ns, spatial resolution of 30 μm/pixel). The streak time and space resolution were 10 ns/pixel and 50 μm/pixel, respectively. An Ar laser (ion laser technology) with a narrow band (±5 nm) filter was used as a backlighting source.

Typical wave forms of I_d, ΔV_{res}, power, and deposited energy in the case of a 10 mm i.d. Cu wire array are presented in Fig. 2. Similar wave forms and discharge parameters were obtained in the case of a 20 mm i.d. Cu wire array explosion. One can see that the wire explosion begins at the current maximum [9], at ≈ 3 μs with respect to the beginning of the discharge current at $I_d \approx 90$ kA, which corresponds to a current density of ≈ 7 MA/cm^2. At the time of the beginning of the explosion, the deposited energy was ≈ 2 kJ (deposited energy density of ≈ 2.5 kJ/g). During the wire explosion (decay of the discharge current) the deposited energy was ≈ 1.8 kJ (the total deposited energy density ≈ 4.8 kJ/g).

A typical shadow streak image of the converging SW is presented in Fig. 3 for a 20 mm i.d. Cu wire array explosion.

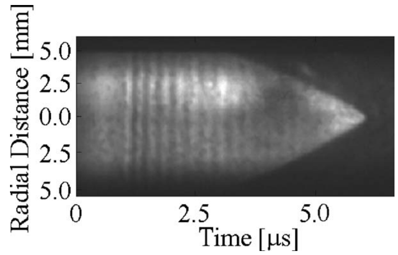

FIG. 3. Typical shadow streak image of the converging cylindrical shock wave for 12 Cu wire an arrays of 20 mm i.d. and 20 mm height. The Cu wire diameter ≈ 0.2 mm.

One can see that at the smaller radii the SW accelerates. Shadow frame images of the SW, taken along the z axis at radii $0.1 \leq r \leq 2$ mm, showed that the implosion wave front is very close to circular. Also, the obtained recent data [10] showed uniformity along the z axis of the SW produced by a single wire explosion. Thus, one can consider the converging SW as cylindrically symmetrical although it was generated by individually exploded wires. The streak and frame shadow images of converging SW allowed us to estimate the full time-of-flight (TOF) measurement of the SW up to $r=0.1$ mm. The uncertainty in the estimation of the TOF, ±150 ns, was determined by the uncertainty in establishing the instant at which the SW is generated by the exploding wire array, whereas the time of the arrival of the SW at the 0.1 mm radius was measured accurately by using a short 30 ns exposure time of the framing camera.

The measured TOF of the SW was used for an estimation of the pressure at the SW front by three independent methods. The first method based on the Whitham model [11], ignores the boundary conditions dictated by the exploding wire, and the flow parameters are determined by the initial Mach number of the converging SW at the boundary of the array. The change in the velocity of the converging SW is then governed by the implosion geometry. The latter determines the rate of the energy density accumulation at the SW front by way of its propagation towards the axis. For the converging cylindrical SW one can calculate the SW velocity at different distances from the axis and the TOF of the SW to these distances. This model assumes isentropic flow and therefore requires only the adiabatic constant of the considered material. We used a standard equation of state (EOS) of water: $p-p_0=A[(\rho/\rho_0)^n-1]$, where p_0 is the pressure at the normal density $\rho_0=1$ g/cm^3, $A=3$ kbar and $n=7.15$ is the adiabatic constant of the water. This EOS is correct up to densities ≈ 1.8 g/cm^3 corresponding to pressure $p=0.2$ Mbar. The velocity of the SW at the 0.1 mm radius was calculated by choosing the appropriate initial SW velocity at the boundary of the array which would give the same TOF as estimated in the experiment. For example, in the case of 10 mm i.d. array, the experimentally estimated TOF was in the range of 1.65 ± 0.15 μs.

One of the main assumptions of the Whitham model is that the source does not influence the propagation of the SW front. However, during the time of the convergence, the discharge channel is still actively expanding [9]. Moreover, this is the period during which a significant part of the energy deposition takes place [see Fig. 2(a)]. Thus the validity of the

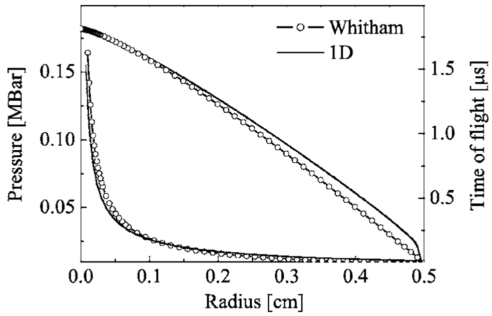

FIG. 4. TOF and pressure of the SW as a function of its distance from the axis calculated by the Whitham model and 1D hydrodynamic calculation for the case of the total TOF of 1.8 μs.

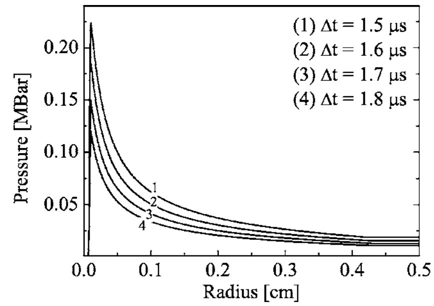

FIG. 5. Radial pressure profiles for different total TOFs at the moment of the SW arrival at 0.1 mm radius obtained using the 1D hydrodynamic calculation.

application of the Whitham model to this problem is questionable. Therefore, a straightforward one-dimensional (1D) hydrodynamic calculation implying the "cross" scheme [12] was run. Here two options for the specification of boundary conditions on the exploding wire surface were implied, namely, either that of the converging boundary velocity or that of the pressure on the exploded wire boundary. The values of the boundary velocity or pressure were chosen such that the calculated TOF was the same as the TOF obtained in the experiment. The two types of boundary conditions result in a similar distribution of the flow parameters for a matching experimental value of TOF.

The results of the calculation of the TOF and SW pressure versus the distance from the axis based on these two methods for the case of maximal experimentally estimated TOF of $\approx$1.8 μs are shown in Fig. 4. In this case, the boundary condition chosen in 1D calculation was the pressure specification at the exploded wire boundary. As expected, the active channel model gives a somewhat different result from the Whitham model. Namely, the SW velocity in the vicinity of the discharge channel where the SW accelerates from zero velocity is smaller for 1D calculation. However, since the TOF of the SW should be the same for both models, at the remaining distance the velocity of the 1D model SW is larger

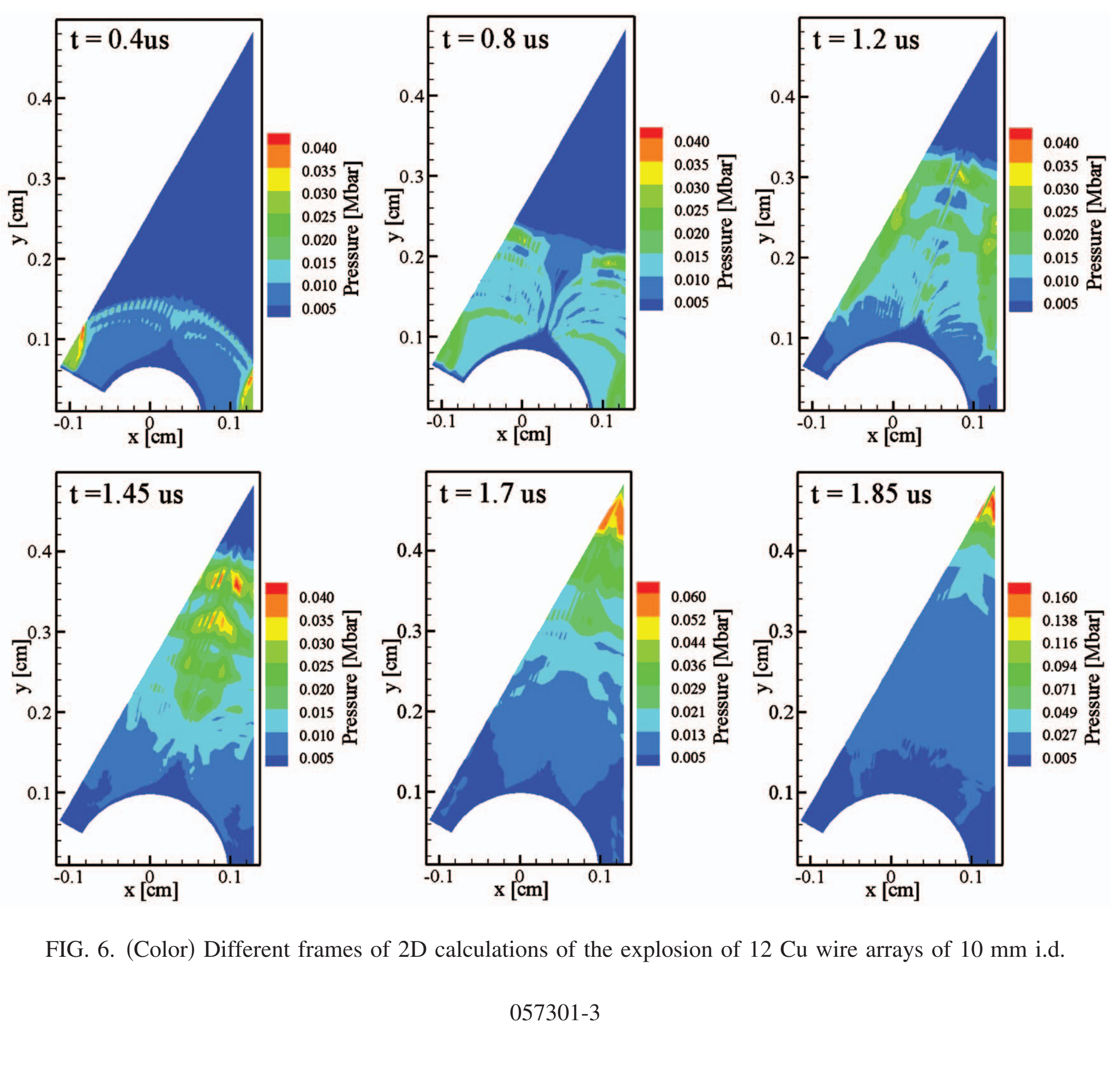

FIG. 6. (Color) Different frames of 2D calculations of the explosion of 12 Cu wire arrays of 10 mm i.d.

than in the case of the Whitham model. Therefore, the estimated pressure at the SW front by way of its convergence is slightly larger in the case of the 1D calculation, which is true up 1 mm distance from the axis. Finally, one can see that both models converge to approximately the same pressure of $\approx$180 kbar at the SW front, at r=0.1 mm. The 1D model also allows one to calculate the flow parameters after the reflection from the axis. For instance, in the case of 1.8 μs TOF, the maximum estimated value of the pressure achieved at the moment the SW reflection reaches the extremely high value of $\approx$2 Mbar. In addition, for the known pressure and velocity at the array boundary, 1D model calculations showed that almost 20% of the deposited energy is transferred to the mechanical energy of the generated flow [see Fig. 2(b)].

The radial pressure profiles calculated using the 1D model for different TOF at the moment of the SW arrival at 0.1 mm radius are shown in Fig. 5. Here different values of TOF were obtained by choosing different pressures at the exploded wire boundary. One can see that for the range of total TOF 1.5–1.8 μs, the maximal pressure values at 0.1 mm radius vary from 120 to 250 kbar.

Finally, the validity of 1D approximation was checked by running a 2D hydrodynamic calculation based on Shashkov's Lagrangian multidimensional hydrodynamic method [13]. Here a wire has been represented as an expanding cylindrical boundary (see Fig. 6). It was assumed that all the wires expand at the same velocity since the energy is deposited at the same rate in all the wires of the array. Thus, the problem has $2\pi/N_w$ periodicity, where N_w=12 is the number of wires. In this case the solution of the 2D problem was found for a single segment of the cylinder with the boundary condition of zero normal velocity on the sides of the segment. In Fig. 6 one can see how an initially convex cylindrical wave is gradually converted to a concave cylindrical wave due to multiple reflections from the side segment walls and multiple collisions of the reflected waves with themselves. The velocity of the expanding wire boundary is chosen such that the calculated TOF matches the experimentally estimated value of 1.8 μs. The maximal calculated value of the SW pressure at r=0.1 mm is $\approx$160 kbar which satisfactorily agrees with the results obtained by the 1D calculation and the Whitham model for a similar TOF. The comparison of the three methods shows that the flow near the axis can be considered one dimensional and that the major parameter that determines the value of the pressure on the axis is the total TOF.

In conclusion, we have demonstrated that even at a preliminary stored energy of a few kJ, underwater electrical discharge of cylindrical wire array in the form of a zigzag can be used efficiently for the generation of sub-Mbar pressure at the axis of a converging cylindrical SW. By increasing the stored energy and the energy deposition rate [8], one might achieve significantly larger pressures on the axis of the imploding wire array. Such extremely high pressure can be used in experiments on plasma heating and confinement and in studies of different material transport coefficients and EOS.

This research was supported by The Israel Science Foundation (Grant No. 1210/04).

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