Recent Results of the Research of Underwater Electrical Explosion of Wires/Wires Arrays

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[2]J. Struska, [2]Y. Yao, [3]B. Lukic, [3]A. Rack, [4]M. Liverts, [5]D. M. Kozlov

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Wire electrical explosion is characterized by:

- *Current density:* $10^6 - 10^{10}$ *A/cm^2*
- *Current pulse duration:* $10^{-4} - 10^{-8}$ s
- *Power:* $10^6 - 10^{13}$ *W*
- *Delivered Energy:* $10^2 - 10^6$ *J*
- *Energy density deposition:* *100 kJ/cm^3*
- *Ultra-fast heating of metals:* *dT/dt > 10^{11} ^{0}K/s*
- *Magnetic field:* 10^3 *T*

Background medium:
vacuum, gas, liquid

Advantages of the Underwater Electrical Wire Explosion

Shunting of the discharge is prevented

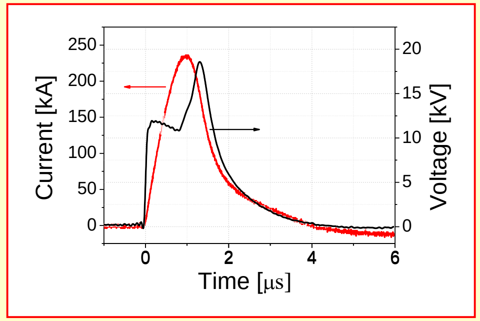
1. High breakdown voltage of the water medium (>300 kV/cm)
2. High pressure of the adjacent water layer (>10 kBar) increases breakdown voltage

Increase in energy density deposition and temperature of the wire

1. High resistance of the water to compression limits the wire radial expansion
2. Substantial decrease in the energy loss to the thin shunting plasma channel and to radiation (water "bath" effect)
3. Due to slow radial expansion, MHD instabilities do not have time to be developed

S. V. Lebedev and A. I. Savvatimski, Review: *Metals during rapid heating by dense currents, Sov. Phys.Usp.* **27**, 749 (1984);
A. V. Luchinskii, *Electrical Explosion of Wires* (Moscow, Russia: Nauka, 1989).
V. I. Oreshkin and R. B. Baksht, *Wire Explosion in Vacuum*, IEEE Trans. Plasm Scie. **48**, 1214 (2020)

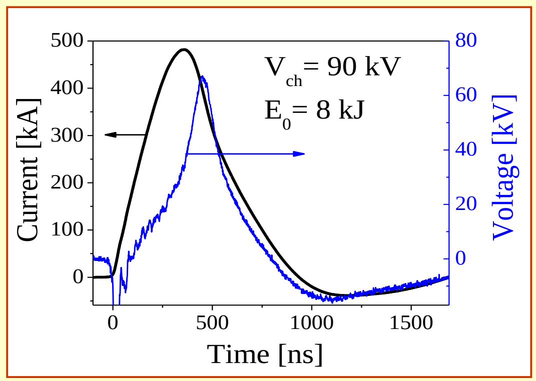
Microsecond Timescale Generator



- Stored energy: 5 kJ
- Rise time: 1200 ns
- Peak current: 300 kA
- Power: 4 GW

$$\frac{dI}{dt} \approx 2.5\times\mathbf{10}^{11}\ \mathrm{A/s},\quad j \approx 5\times10^{8}\ \mathrm{A/cm^2}$$

Sub-microsecond Timescale Generator



- Stored energy: 9.5 kJ
- Current amplitude: 800 kA
- Rise time: 350 ns
- Power: 60 GW

$$\frac{dI}{dt} \approx 2.5\cdot10^{12}\ \mathrm{A/s}\quad j \approx 10^{10}\ \mathrm{A/cm^2}$$

	μsec	nsec
Stored Energy [kJ]	~4.5	~0.7
Current Rise Rate [A/s]	$\sim 2\cdot10^{11}$	$\sim 10^{12}$
Maximal Electrical Input Power [GW]	~5.0	~6.0
Maximal Energy Deposition [eV/atom]	~55	~300
Maximal Generated SW Pressure [kBar]	~20	~100
Maximal DC Temperature [eV]	~3.0	~7.0

Magneto-hydrodynamic (MHD) simulation

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial (r\rho v)}{\partial r} = 0$$ Mass conservation

$$\rho\frac{\partial v}{\partial t} + \rho v\frac{\partial v}{\partial r} = -\frac{\partial p}{\partial r} - \frac{1}{c} j_z B_\varphi$$ Momentum conservation

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho v\frac{\partial \varepsilon}{\partial r} = -p\frac{1}{r}\frac{\partial (rv)}{\partial r} + \frac{j_z^2}{\sigma} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\kappa\frac{\partial T}{\partial r}\right)$$ Energy conservation

$$\frac{1}{c}\frac{\partial B_\varphi}{\partial t} = \frac{\partial E_z}{\partial r}; \quad j_z = \frac{c}{4\pi r}\frac{\partial (rB_\varphi)}{\partial r};$$ Maxwell equations

$$j_z = \sigma E_z$$ Ohm law

$$P = P(\varepsilon,\rho); \quad T = T(\varepsilon,\rho);$$ Equations of state (EOS)

$$\sigma = \sigma(\varepsilon,\rho); \quad \kappa = \kappa(\varepsilon,\rho);$$ Transport parameters

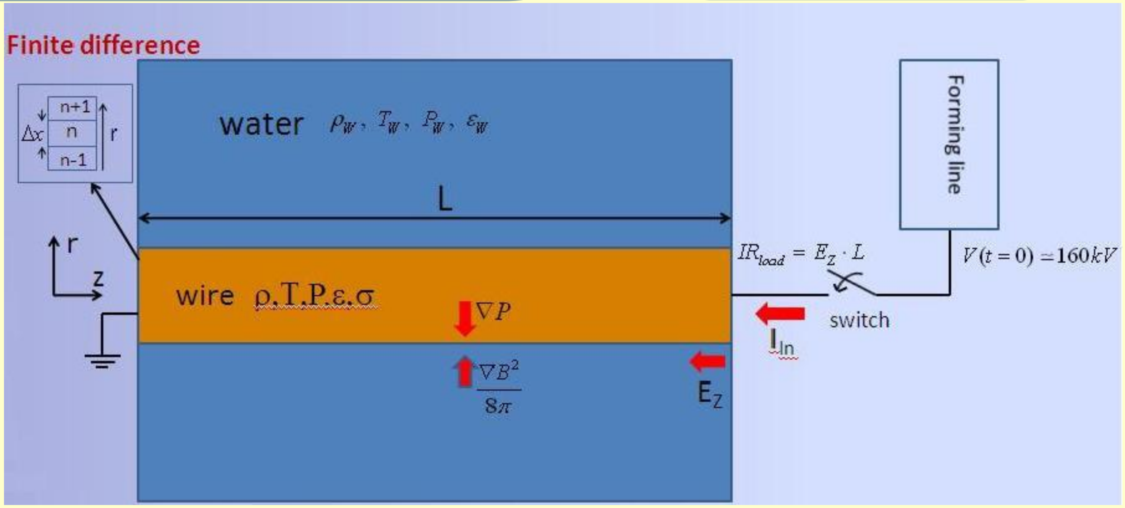
EOS:

SESAME

Electrical/thermal conductivity:

- Sesame
- Desjarlais (2001)
- BKL (1976)
- Wiedemann-Franz

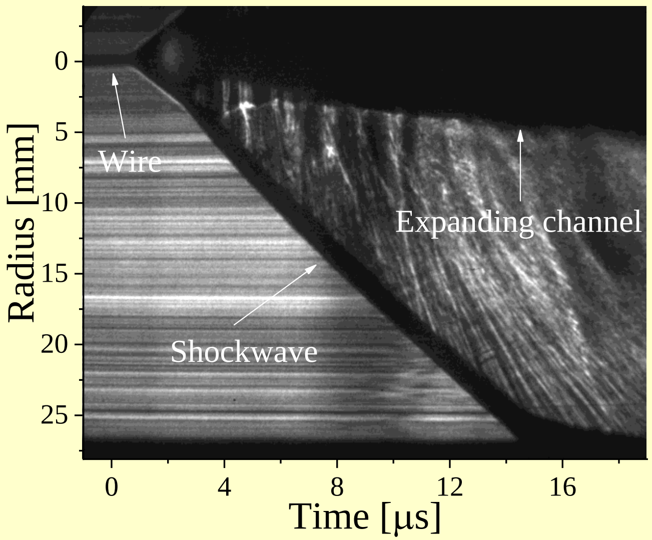
Temperature, density, internal energy, pressure and conductivity are calculated self-consistently



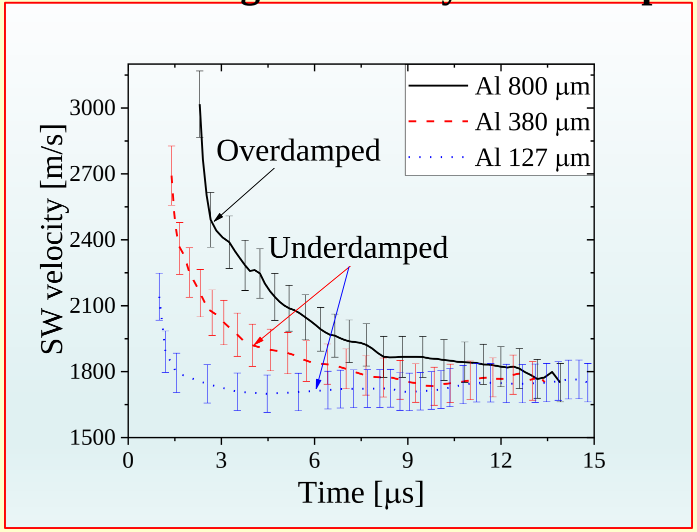
V. Oreshkin, *et al*., Tech. Phys. **49**, 843 (2004); A. Grinenko, V. Tz. Gurovich, A. Saypin, S. Efimov, V. I. Oreshkin, and Ya. E. Krasik, *Strongly coupled copper plasma generated by underwater electrical wire explosion*, Phys. Rev. E 72, 066401 (2005); G. Bazalitski, V. Ts. Gurovich, A. Fedotov-Gefen, S. Efimov and Ya. E. Krasik, *Simulation of converging cylindrical GPa-range shock waves generated by wire array underwater electrical explosion*" Intern. J. Shock Waves, Detonations and Explosions, **21**, 321 (2011).

Which discharge mode is the most efficient for shock generation?

Streak image of the exploding Al wire



Velocities of shocks generated by Al wire explosions



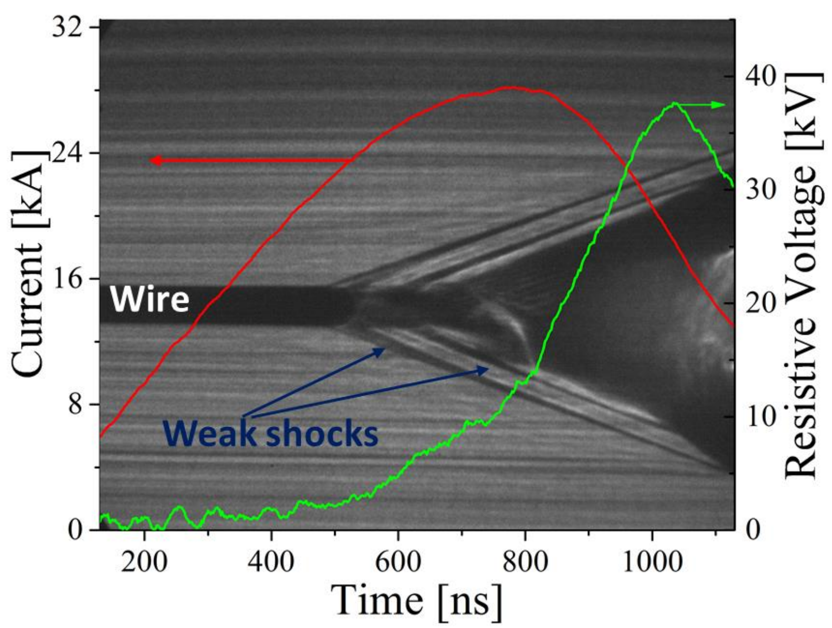
Most efficient shock generation is realized for an almost critically damped discharge which is characterized by the *largest energy and energy deposition rate* during the vapor-low ionized plasma phase transition

	Energy density [kJ/g]	Energy density deposition rate [kJ/(g·s)]×10^6	Energy density per unit area at maximal power [kJ/(g·cm^2)]×10^9
μs-timescale Copper wire: ∅500μm, 23 mm length	65	75	2.3
sub-μs timescale Copper wire: ∅250μm, 23 mm length	40	201	10.3

A. Rososhek , S. Efimov, A. Virozub , D. Maler , and Ya. E. Krasik, *Particularities of shocks generated by underwater electrical explosions of a single wire and wire arrays*, Appl. Phys. Lett. **115**, 074101 (2019). D. Maler, S. Efimov, M. Liverts, A. Virozub and Ya. E. Krasik, “Addressing the critical parameters for overdamped underwater electrical explosion of wire”, Phys. Plasmas 29, 102703 (2022).

Weak shocks onset - unique method for studying phase transitions

Laser backlit streak image overlapped with current and resistive voltage waveforms



1st shock onset, [ns]	Shock wave velocity, [m/s]	2nd shock onset, [ns]	Shock wave velocity, [m/s]
490	1580	600	1690

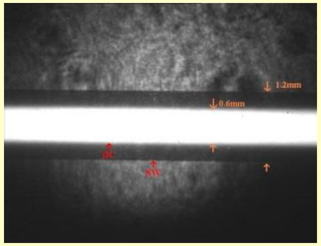
$\Delta\epsilon_f$, [J/g]	ΔH_f, [J/g]	$\Delta\epsilon_e$, [J/g]	ΔH_e, [J/g]
375	390	540	12230

1. **Energy density deposited into the wire prior to the onset of the 1st weak shock is almost equal to the enthalpy of fusion**

2. **At the onset of the 2nd weak shock, the deposited energy density is only a fraction of the enthalpy of vaporization. Thus only part of the entire wire experiences this phase transition which results in two-phase coexistence.**

A. Rososhek, S. Efimov, S. V. Tewari, D. Yanuka, and Ya. E. Krasik, "Phase transitions of copper, aluminum, and tungsten wires during underwater electrical explosions", Phys. Plasmas **25**, 102709 (2018)

Equation of States and Conductivity models



Cu wire , l=50mm, Ø=0.1mm, t=188ns

Experimental parameters

$\rho \sim 0.1 - 10$ g/cm^3

$T \sim 0.03 - 8$ eV

$P \sim 0 - 0.4$ Mbar

$\varepsilon \sim 0 - 500$ eV/atom

$\sigma \sim 5 \cdot 10^4 - 6 \cdot 10^7$ S/m

Cu wire

EOS: SESAME data base

S. P. Lyon and J. D. Johnson,"SESAME, LANL EOS" Report No. LA UR-92-3407

Conductivity models

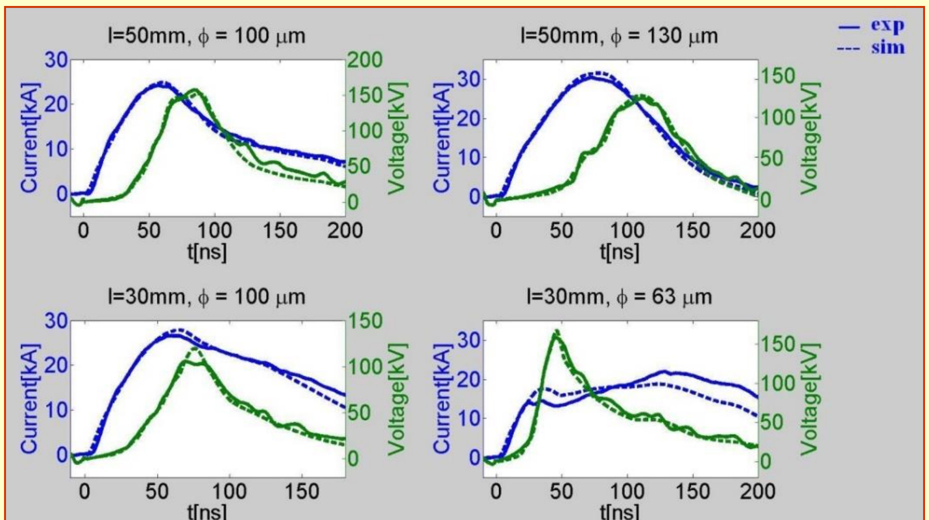
- Semi-empirical model (BKL)

Yu. D. Bakulin, V. F. Kuropatenko, and A. V. Luchinskii, Sov. Phys. Tech. Phys. **21**, 1144 (1976).

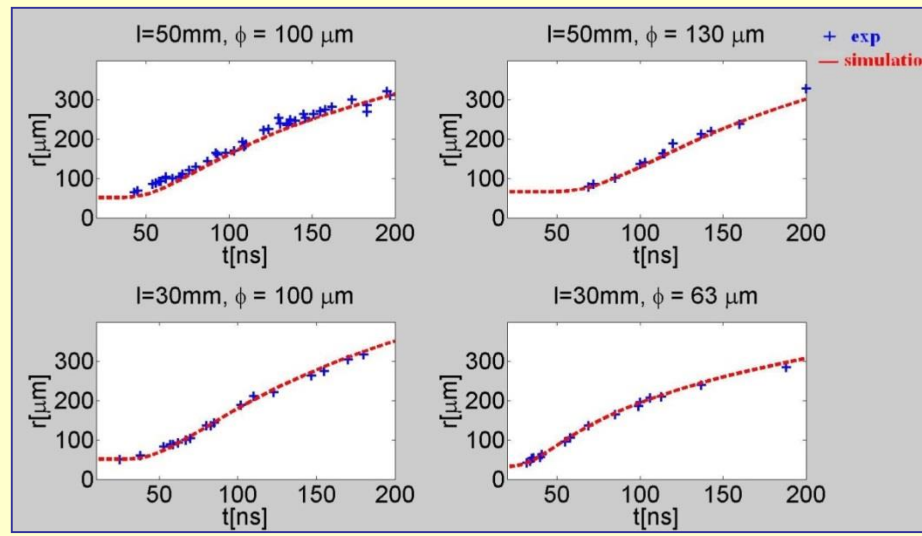
- LMD and QLMD models

M. P. Desjarlais, Contrib. Plasma Phys. **41**, 267 2001.
M. P. Desjarlais, *et al*., Phys. Rev. E **66**, 025401 (2002)

Conductivity values are obtained by fitting simulated current and voltage waveforms to experimental data



Pressure values are obtained by fitting simulated wire expansion to experimental data

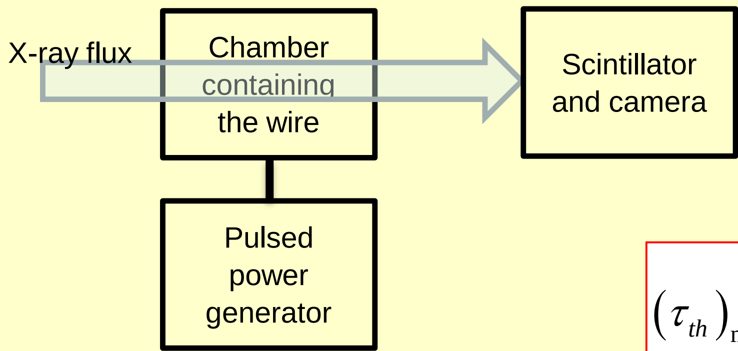


D. Sheftman and Ya. E. Krasik, *Investigation of electrical conductivity and equation of state of non-ideal plasma through underwater electrical wire explosion*, Phys. Plasmas **17**, 112702 (2010); D. Sheftman and Ya. E. Krasik, Evaluation of electrical conductivity and equations of state of non-ideal plasma through microsecond timescale underwater electrical wire explosion, Phys. Plasmas 18, 092704 (2011).

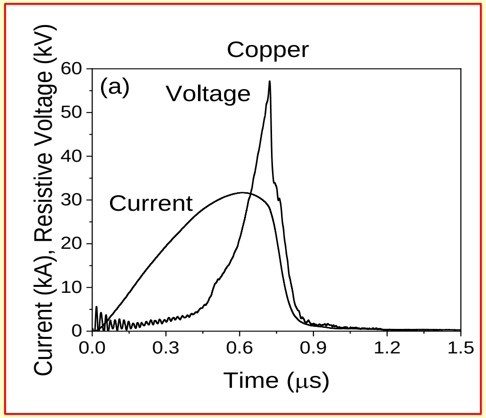
X-ray radiography of the overheating instability

Synchrotron radiation: 20 – 50 keV. Space resolution down to 8 μm.

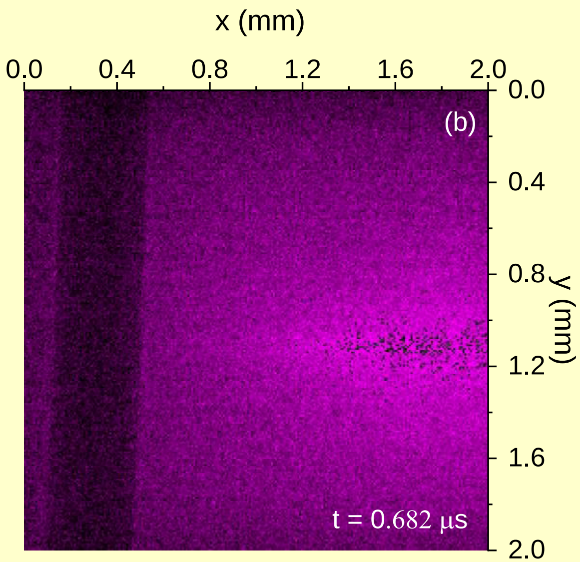
Sketch of the experimental setup

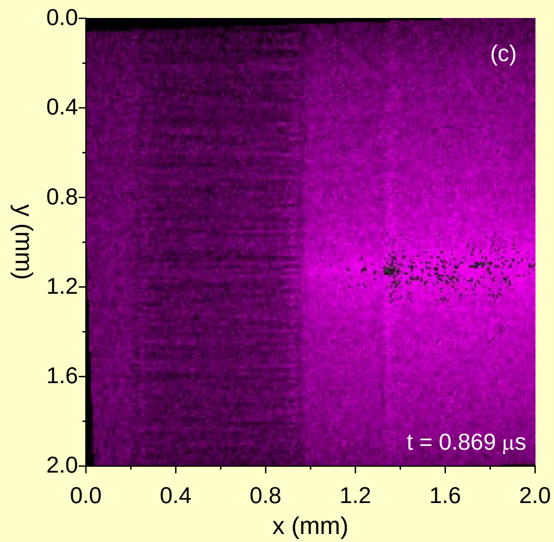


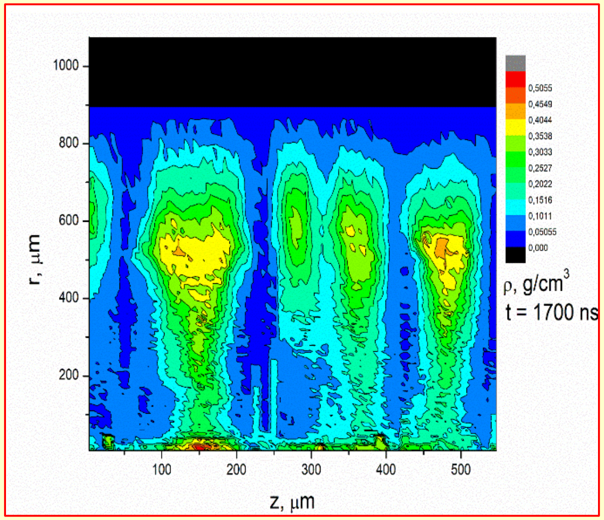
Current and resistive voltage for copper wire explosion



$$\left(\tau_{th}\right)_{\min} \approx \frac{\rho c_V}{j^2}\left(\frac{\partial \delta}{\partial T}\right)^{-1}$$







Overheating instability was obtained during submicrosecond wire explosion

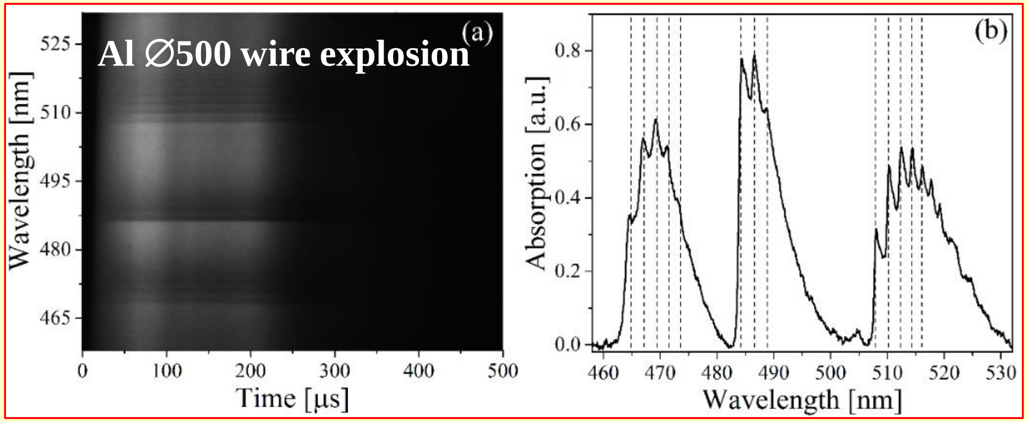
D. Yanuka, A. Rososhek, S. Theocharous, S. N. Bland, Ya. E. Krasik, M. P. Olbinado, A. Rack, and E. V. Oreshkin, *X-ray radiography of the overheating instability in underwater electrical explosions of wires*, Phys. Plasmas **26**, 050703 (2019); D. Yanuka, S. Theocharous, S. Efimov, S. N. Bland, A. Rososhek, Ya. E. Krasik, M. P. Olbinado, and A. Rack, *Synchrotron based X-ray radiography of convergent shock waves driven by underwater electrical explosion of a cylindrical wire array*, J. Appl. Phys. **125**, 093301 (2019).

Shockwave acceleration by Al combustion

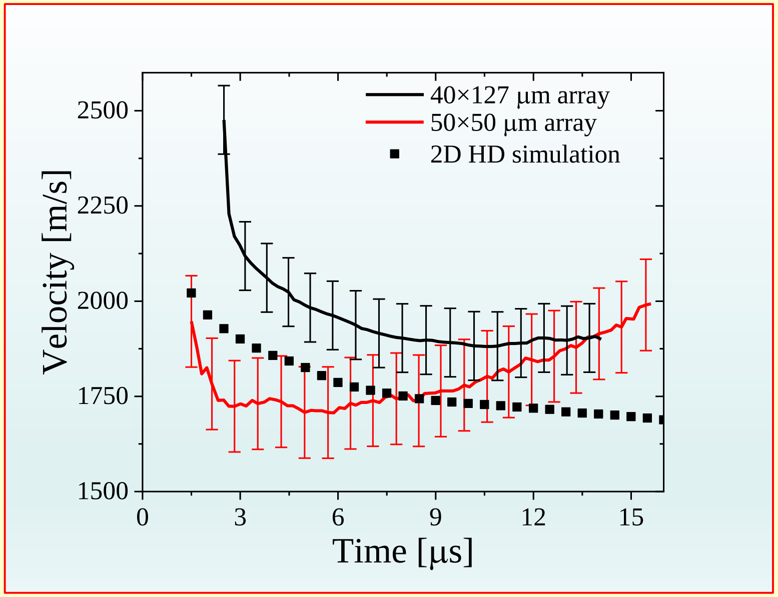
$$2Al(s) + 3H_2O(l) = Al_2O_3(s) + 3H_2(g) + (\leq 64\frac{kJ}{g})$$

(a) streak image of the time-resolved spectrum

(b) absorption bands of *AlO*: transitions Δv (0, ±1)



Shock velocity generated by Al wire planar array explosion

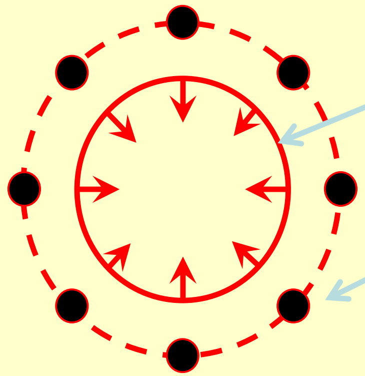


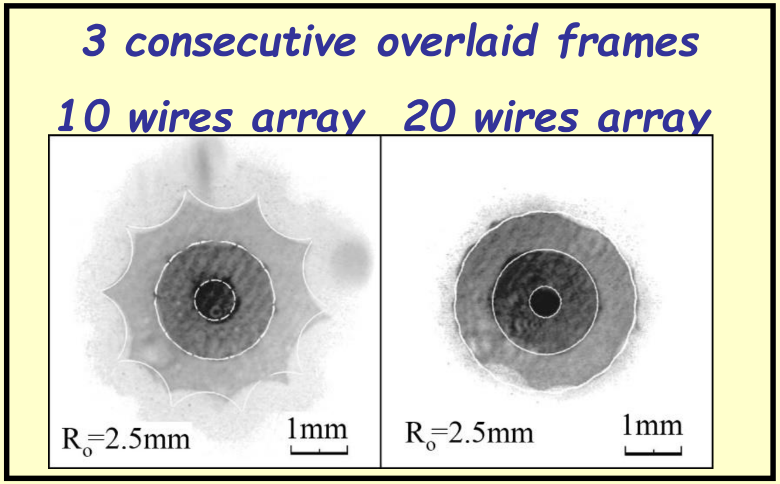
Decreasing the wire diameter and increasing the current density lead to a shorter time delay of combustion ignition ≤2 μs and higher rate of Al combustion, i.e. up to ~1.3×10^3 g/s

The shock can be accelerated by Al wires efficient combustion

A. Rososhek , S. Efimov, A. Goldman, S. V. Tewari, and Ya. E. Krasik, *Microsecond timescale combustion of aluminum initiated by an underwater electrical wire explosion*, Phys. Plasmas **26**, 053510 (2019)

Cylindrical and Spherical SSW Implosion





Self-similarity

Initial energy

$$P_{SW}\left(R_{SW}\right) \propto \frac{E_0}{R_0^{\beta}} R_{SW}^{-\alpha}$$

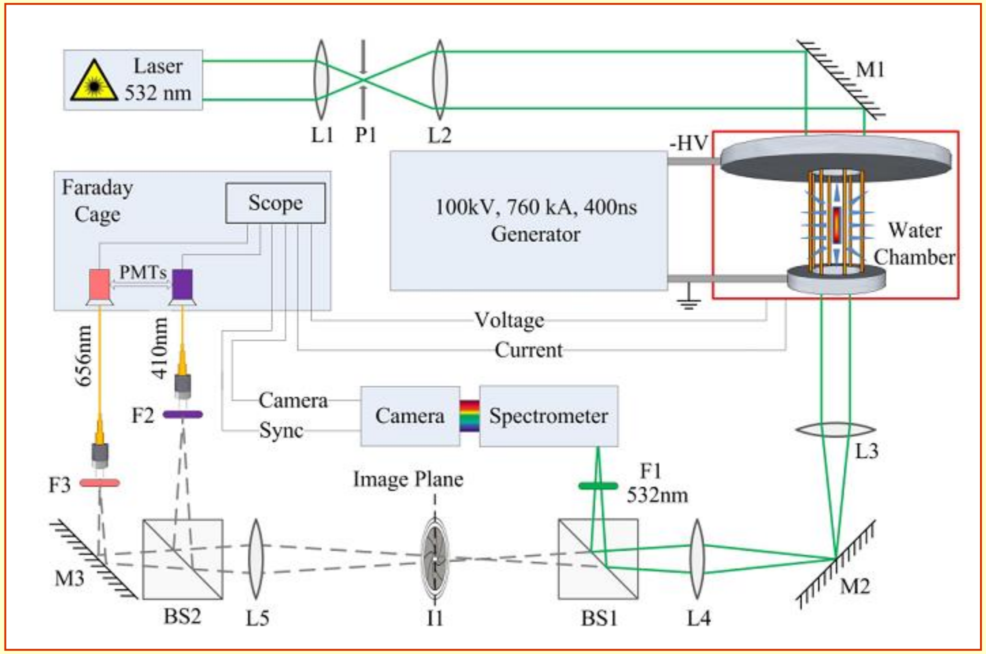
Initial radius

α~1.33, β=1.67 - spherical implosion;
α~0.67, β=1.33 - cylindrical implosion

Due to the **cumulation of the converging SSW** it is possible to achieve ultra-high pressure at the axis/origin of implosion <u>in case that SSW keeps its uniformity during the propagation</u>

Ya. E. Krasik, A. Grinenko, A. Sayapin, V. Tz. Gurovich, and I. Schnitzer, *Generation of sub-MBar pressure by converging shock waves produced by underwater electrical explosion of wire array*,. Phys. Rev. **E 73**, 057301 (2006). V. Tz. Gurovich, A. Grinenko and Ya. E. Krasik, *Semi-analytical solution of the problem of converging shock waves*, Phys. Rev. Lett. **99**, 124503 (2007). A. Grinenko, V. Tz. Gurovich and Ya. E. Krasik, *Implosion in water medium and its possible application for the Inertial Confinement Fusion*, Phys. of Plasmas **14**, 012701 (2007). G. Bazalitski, V. Ts. Gurovich, A. Fedotov-Gefen, S. Efimov and Ya. E. Krasik, *Simulation of converging cylindrical GPa-range shock waves generated by wire array underwater electrical explosion*, Intern. Shock Waves, Detonations and Explosions **21**, 321 (2011).

Underwater electrical explosion – Cylindrical wire array

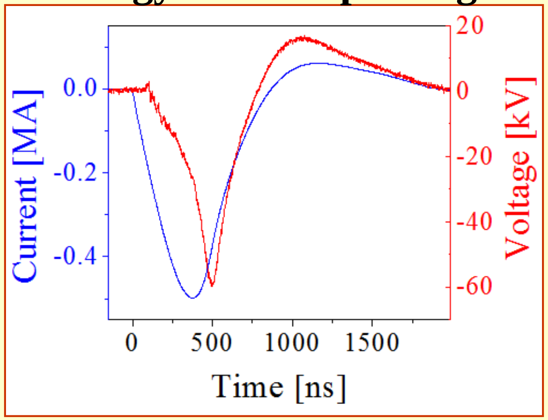


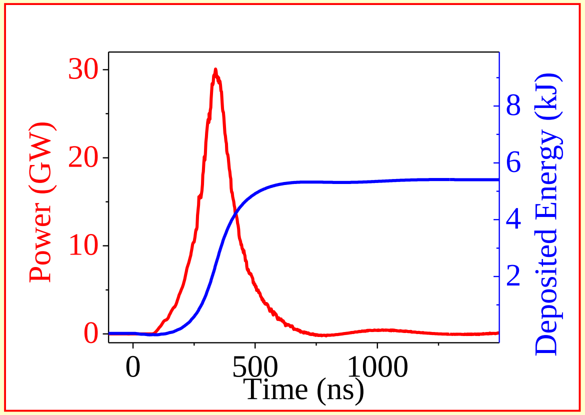
Parameters of electrical wire array

- **Cylindrical array radius 5 - 15 mm**
- **Cylindrical wire array length 20-60 mm**
- **Number of Cu wires: 20 – 60**
- **Diameters of Cu wires: 60 – 140 μm**
- **Wire Array resistance at explosion ≤ 1 Ω**

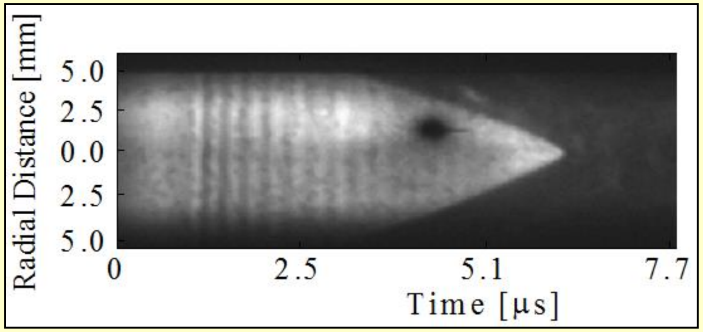
40ty 50μm dia Cu- array

Aperiodical discharge: deposition of ~ 90% of the stored energy to the exploding wires



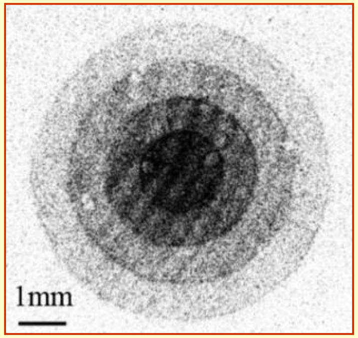


Streak imaging of cylindrical SW implosion

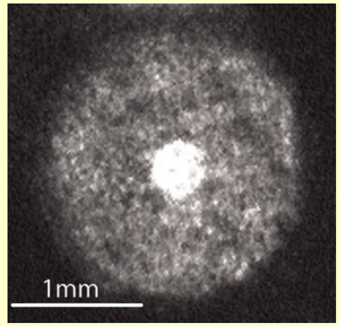


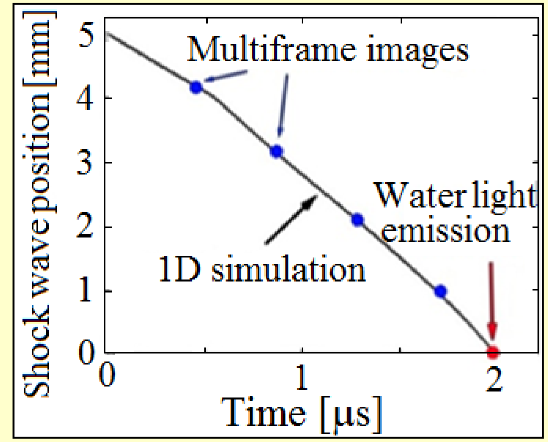
Cylindrical SW Implosion (microsecond generator)

4 shadow images of SW



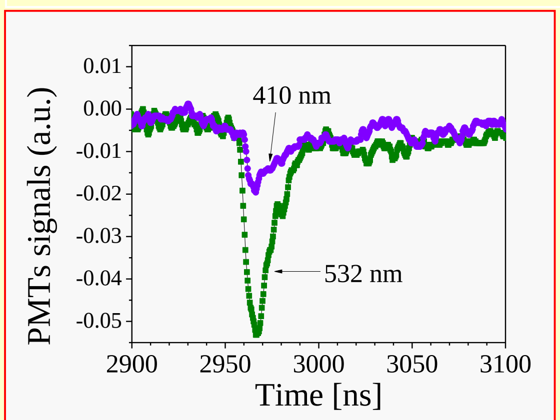
2 shadow images of SW



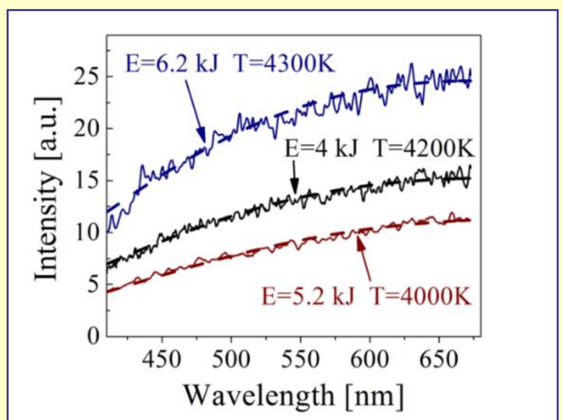


Azimuthal symmetry of converging cylindrical shock was obtained down to 30 μm radius

Water light emission (experiment)



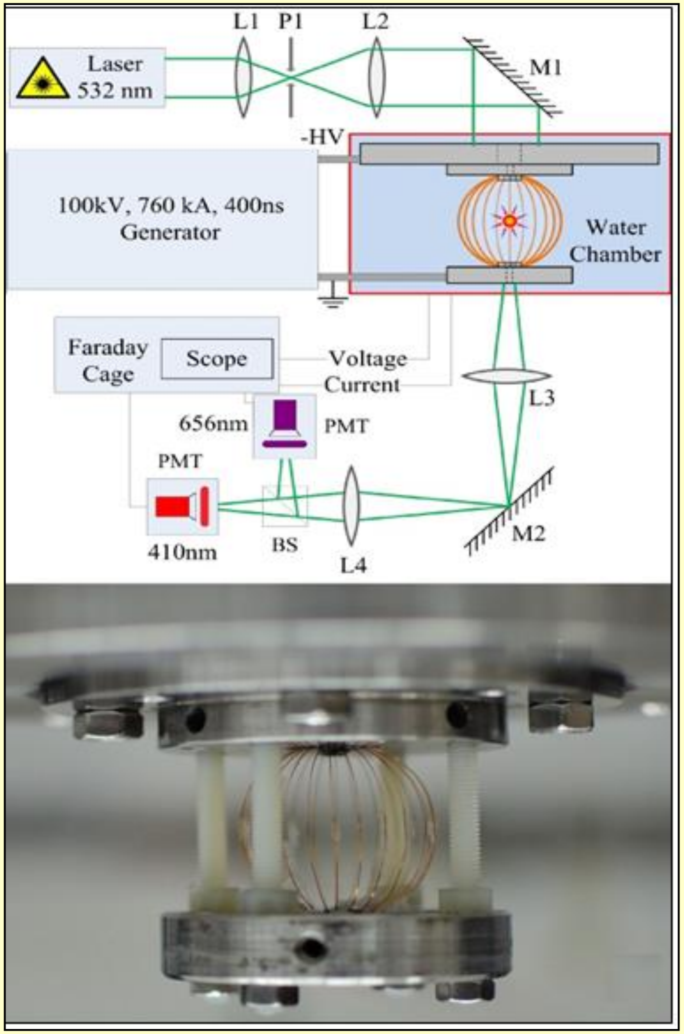
Spectroscopic data: the light emitted by implosion can be characterized by a BB spectrum at **4500±500K** independent of the **deposited energy** or the **average SW velocity**.



This can be related to radiation screening by a thin and low-temperature "water" plasma layer.

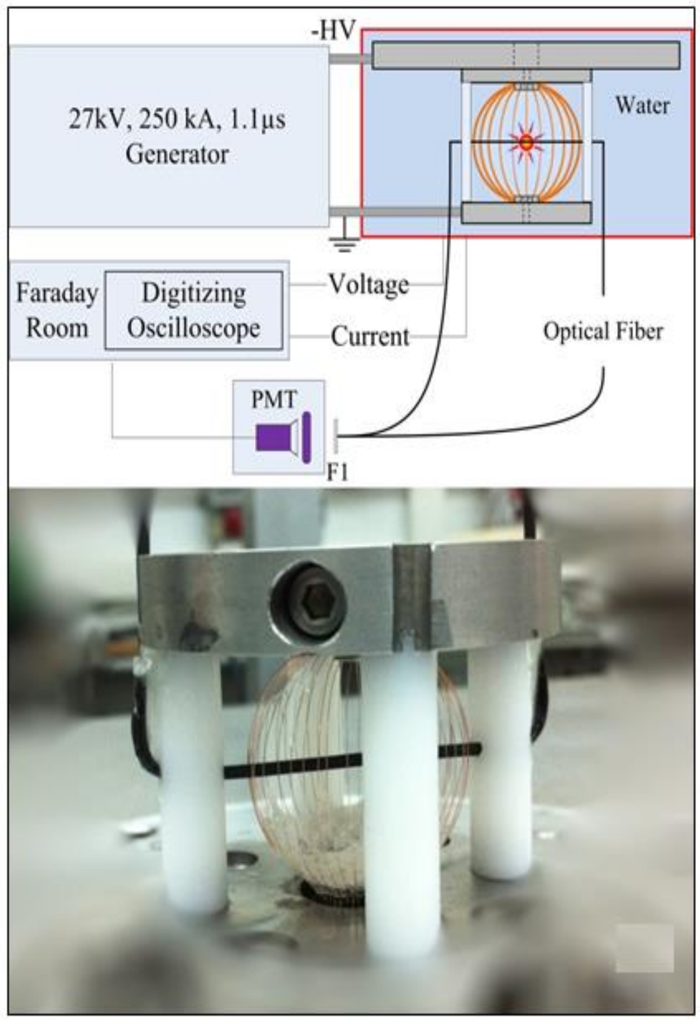
A. Rososhek, D. Nouzman, Ya. E. Krasik, "*Addressing the symmetry of a converging cylindrical shock wave in water close to implosion*", Appl. Phys. Lett. **118**, 174103 (2021).

Experimental setup for Spherical wire array underwater electrical explosion



Pressure estimation using self-similarity of shock convergence:

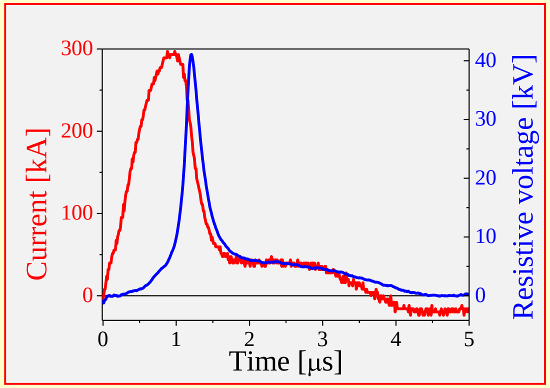
$$p_{sp} \propto E_w \left(r_o^{1.67} \cdot r_c^{1.33} \right)^{-1}$$



O. Antonov, S. Efimov, D. Yanuka, M. Kozlov, V. Tz. Gurovich and Ya. E. Krasik, *Generation of converging strong shock wave formed by microsecond timescale underwater electrical explosion of spherical wire array*, App. Phys. Lett. **102**, 124104 (2013); Ya. E. Krasik, S. Efimov, D. Sheftman, A. Fedotov-Gefen, O. Antonov, D. Shafer, D. Yanuka, M. Nitishinskiy, M. Kozlov, L. Gilburd, G. Toker, S. Gleizer, E. Zvulun, V. Tz. Gurovich, D Varentsov, and M. Rodionova, "*Underwater Electrical Explosion of Wires and Wire Arrays and Generation of Converging Shock Waves*," IEEE Trans. Plasma Scie. **44**, 412 (2016).

Results on the Sub-Microsecond Time Scale

Discharge current and voltage



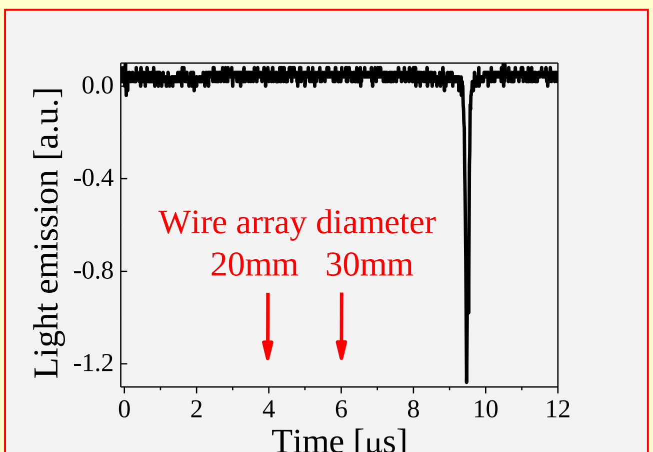
Result of 1D HD simulation assuming symmetry of SSW

Input data: deposited energy density to the wires and TOF of SW

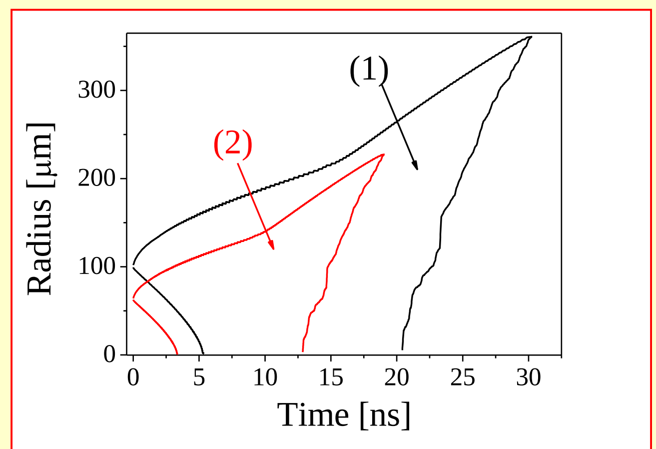
Array parameters	P (10^12 Pa)	δ = ρ/ρ_0	T (eV)
40 Cu wires ∅$_w$114μm,∅20mm	5.5	5.5	24
40 Cu wires ∅$_w$114μm, ∅30mm	4.0	5	17
36 Al wires ∅$_w$152μm, ∅30mm	5.5	5.5	24

P, T and δ given when the SW front reaches r = 5 μm

Water light emission

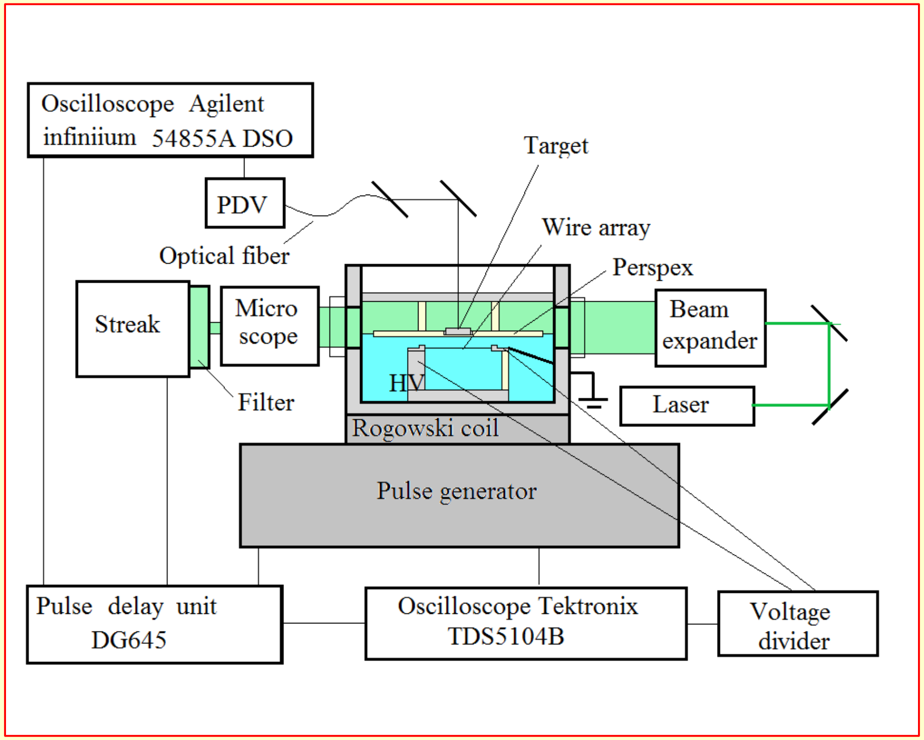


Time evolution of the radial position of a 10^{11} Pa pressure in water generated by **(1) μs-timescale and (2) sub-μs-timescale** electrical explosions of 30-mm Cu wire array.

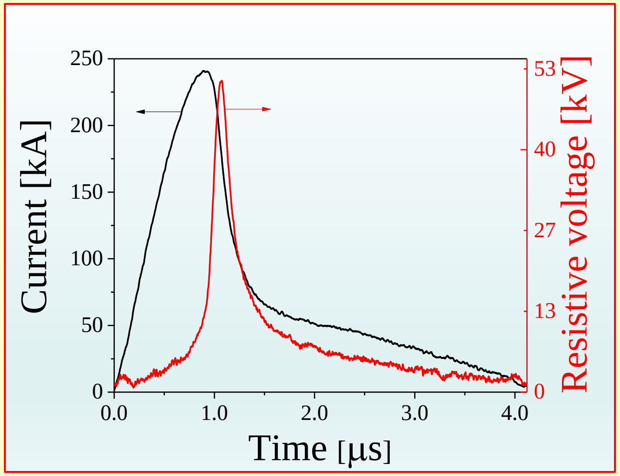


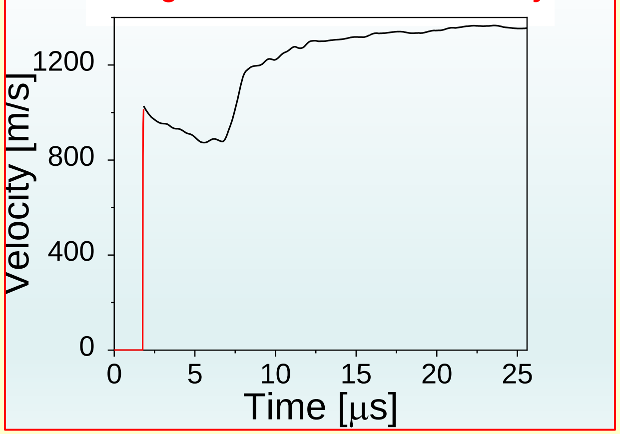
Target acceleration by strong shock wave
Photonic Doppler Velocimetry

Planar Cu wire array



Microsecond timescale experiments

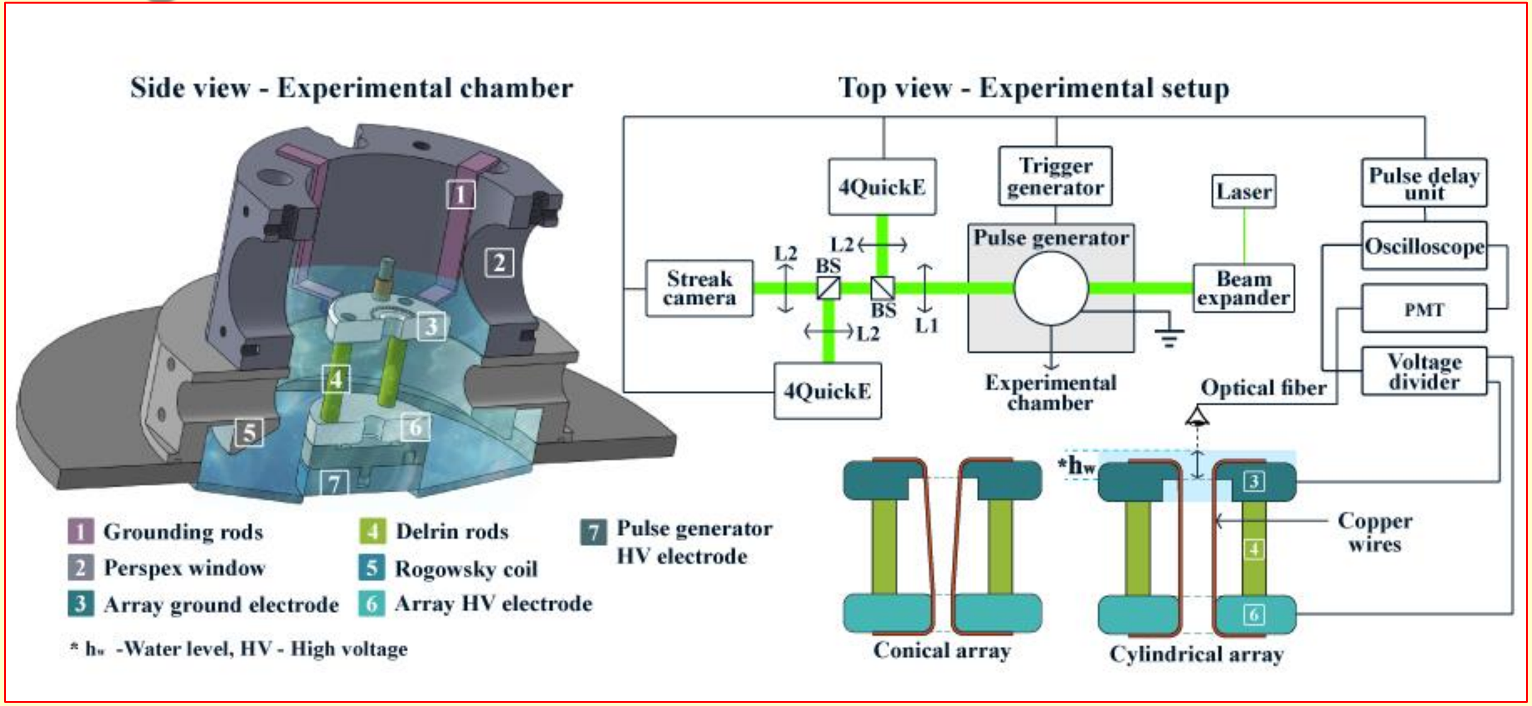


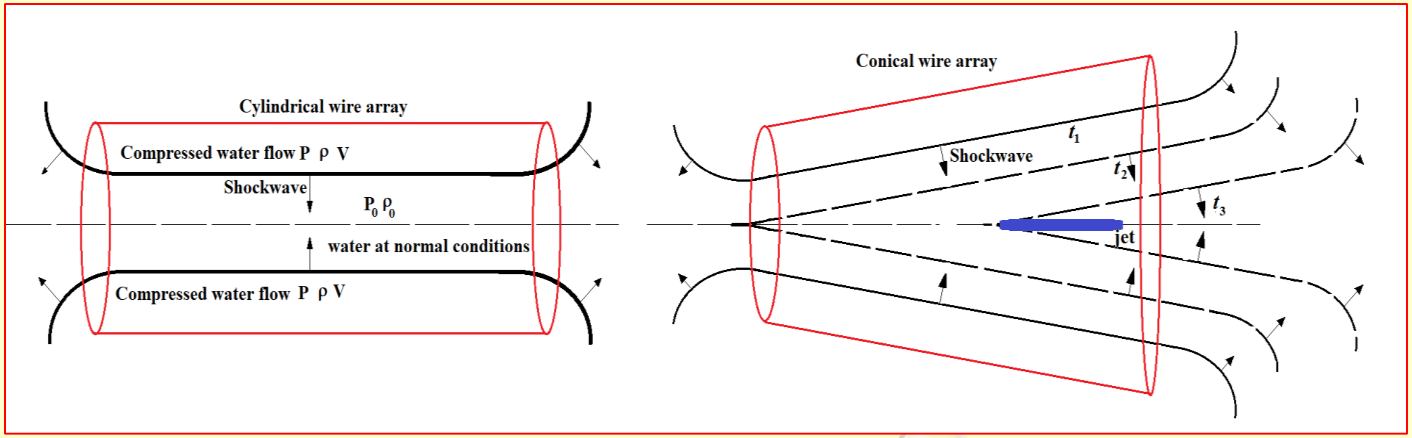


Using the pulse generator with ~6 kJ stored energy, a velocity up to 1.4 km/s of thin targets was achieved with up to 12% efficiency of the energy transfer

D. Maler, A. Rososhek, S. Efimov, A. Virozub, and Ya. E. Krasik, "*Efficient target acceleration using underwater electrical explosion of wire array*", J. Appl. Phys. **129**, 034901 (2021); D. Maler, S. Efimov and Ya. E. Krasik, "*Target acceleration by sub-microsecond underwater electrical explosions of wire arrays*", J. Appl. Phys. **131**, 074902 (2022).

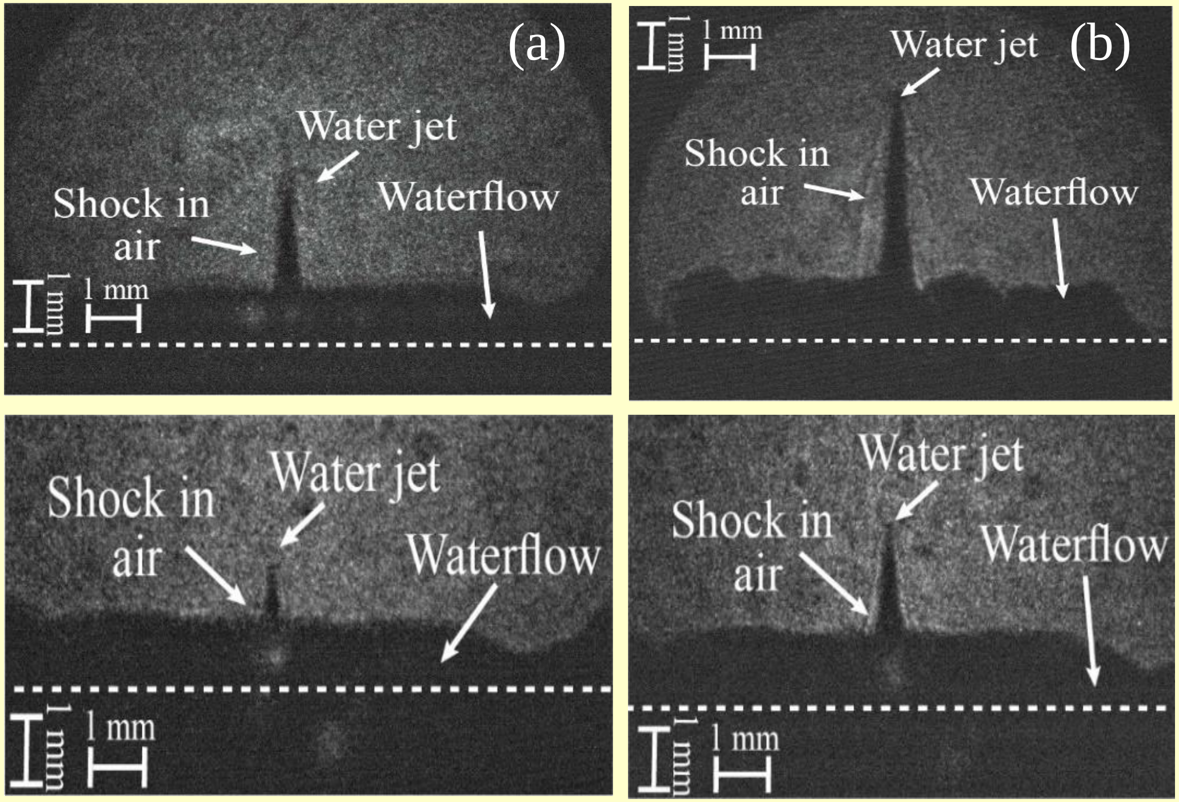
Supersonic cumulative water jets



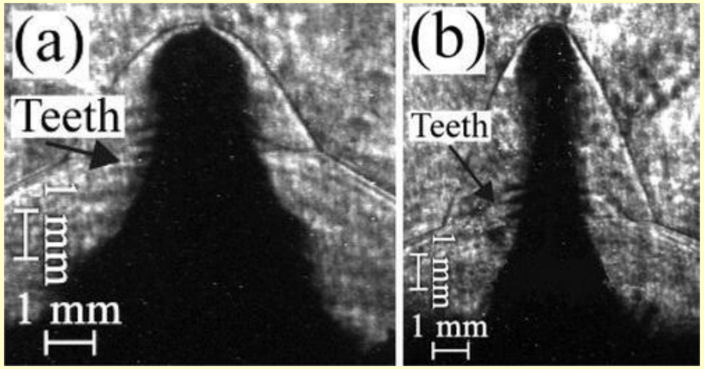


D. Maler, S. Efimov, A. Rososhek, S. N. Bland, and Ya. E. Krasik, "*Generation of supersonic jets from underwater electrical explosions of wire arrays*", Phys. Plasmas **28**, 063509 (2021); D. Maler, M. Kozlov, S. Efimov and Ya. E. Krasik, "*Supersonic jet generation by underwater sub-microsecond electrical explosions of wire arrays*", Phys. Plasmas **29**, 032705 (2022).

Supersonic cumulative water jets



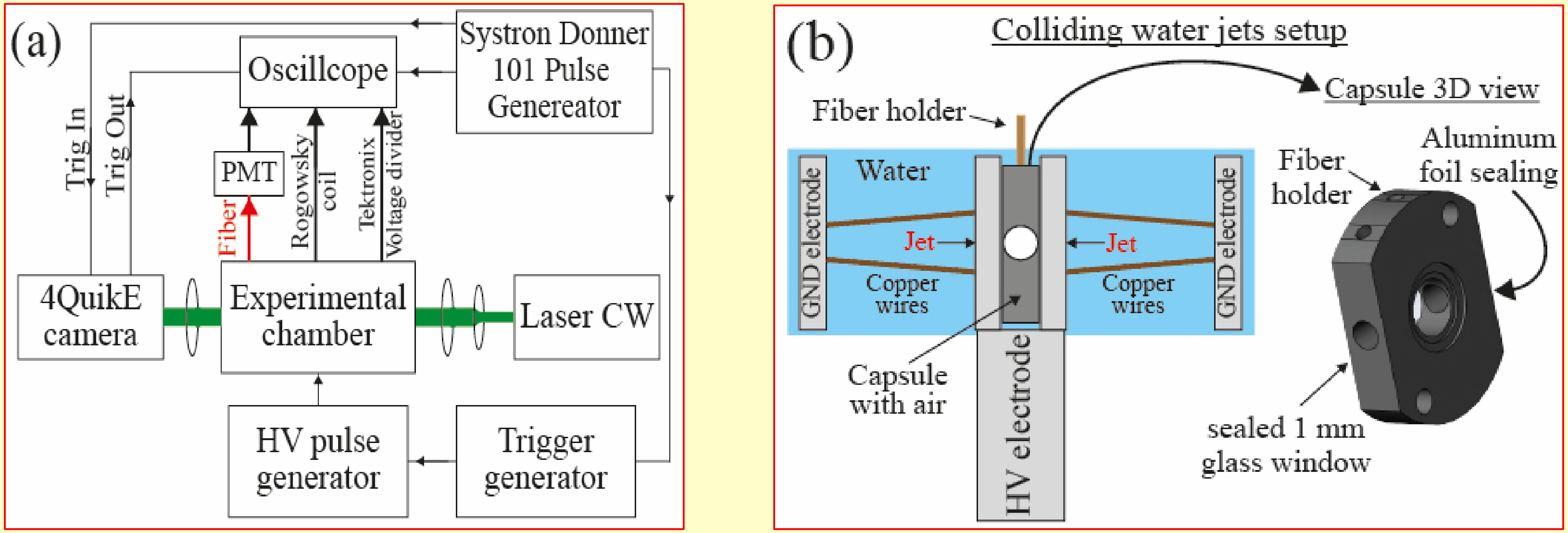
Signatures of Kelvin–Helmholtz HD instabilities on the side boundaries of the fast propagating jet

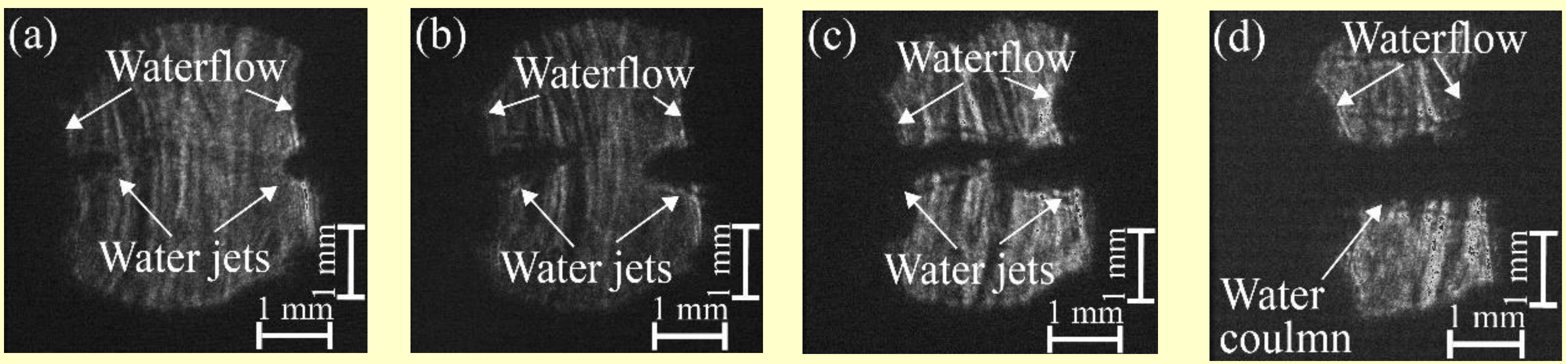


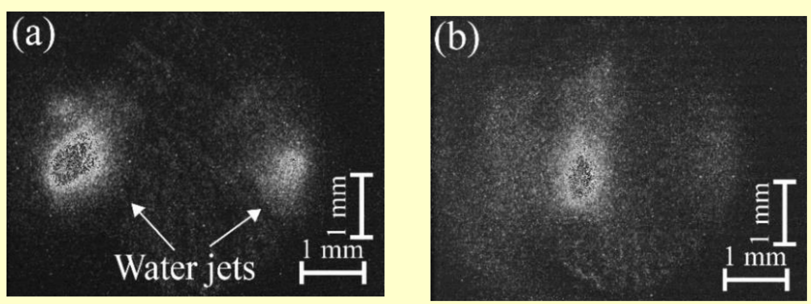
Shadow images of a water jet, generated by the explosion of cylindrical array without a reflector at $t = 4.4\ \mu s$ (a) and at $5.5\ \mu s$ (b); the explosion of a conical array with a reflector at $t = 3.2\ \mu s$ (c) and $3.7\ \mu s$ (d).

Cylindrical array: jet velocity of ~3400 m/s

Conical array: jet velocity of ~4900 m/s



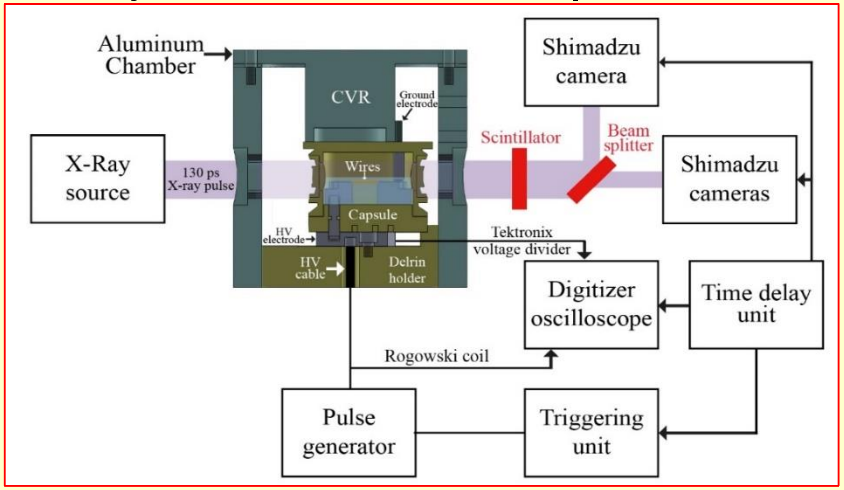




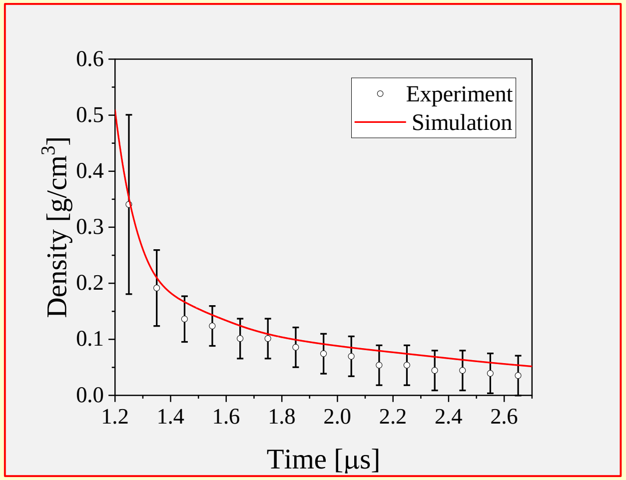
The results of HD simulations show that the water pressure, density and temperature reach ~1.7×10^{10} Pa, ~1.7×10^{3} kg/m^3 and ~2200 K

Recent experiments on the European Synchrotron Radiation Facility

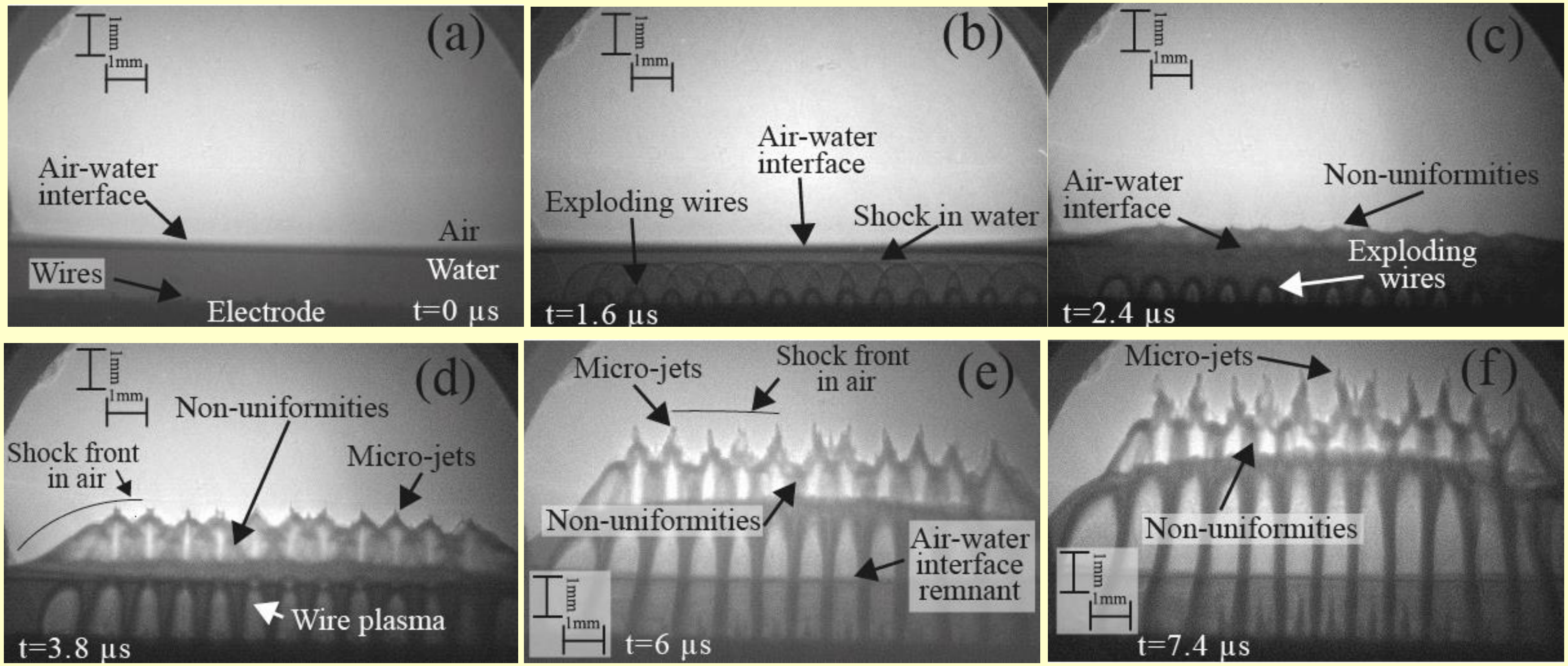
X-ray beam: 20 – 30 keV, 130 ps duration



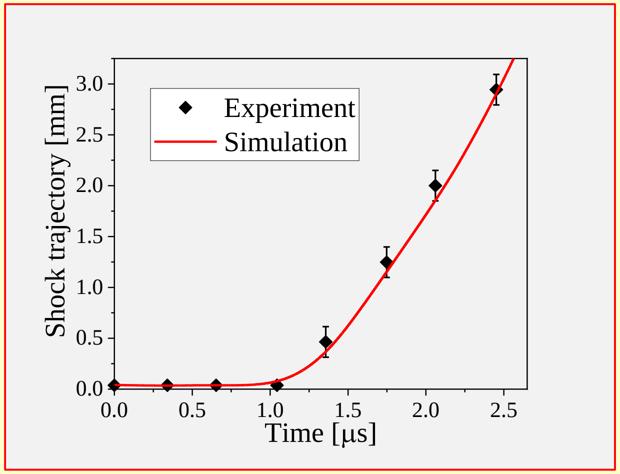
Simulated and experimentally evaluated wire density



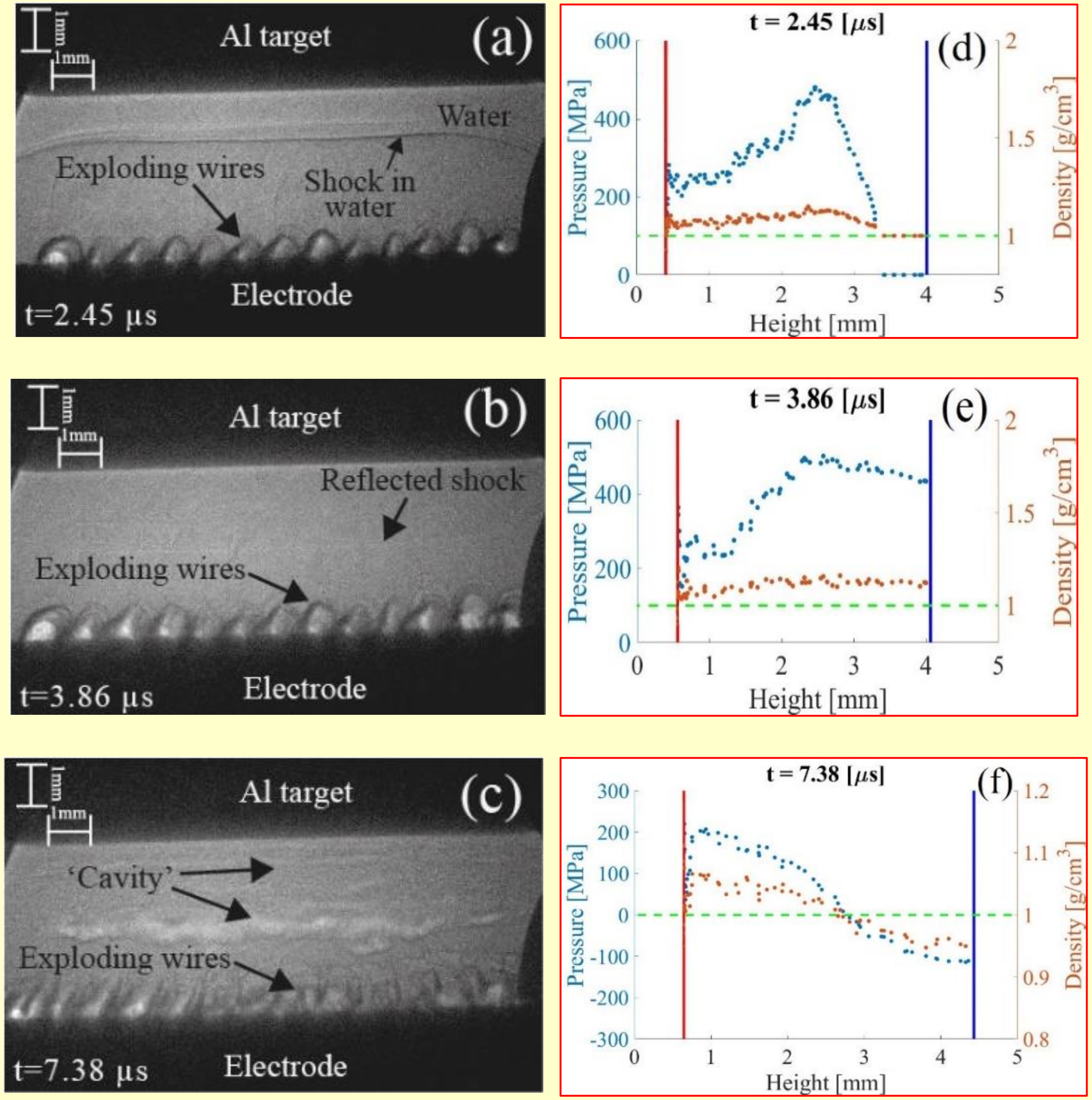
Radiography images of a submerged planar Cu wire array viewed along the wire axis at different times. The air-water interface is at a height of ~1.4 mm with respect to the wire array



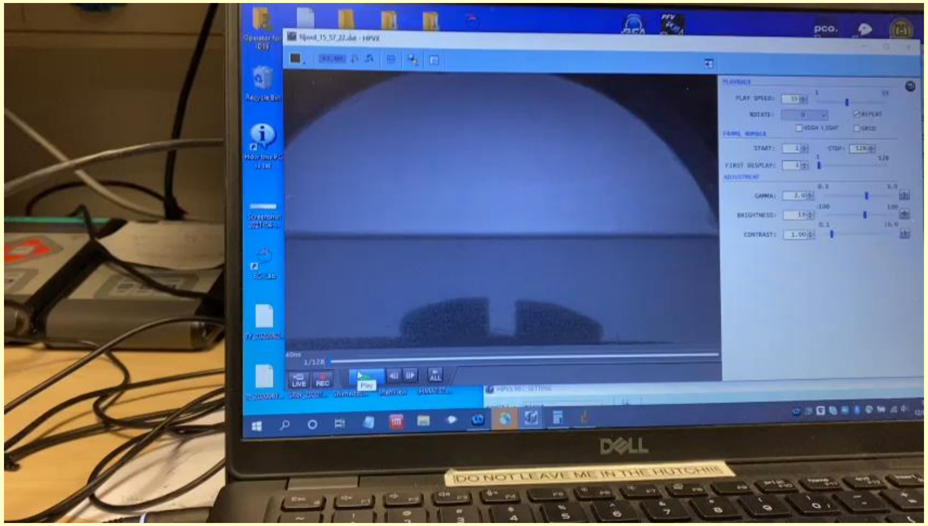
Radiography images of a submerged planar Cu wire array viewed along the wires at different times (a,b,c) and simulated distributions of density and pressure in water and target at different times with respect to the beginning of the discharge current (d,e,f).



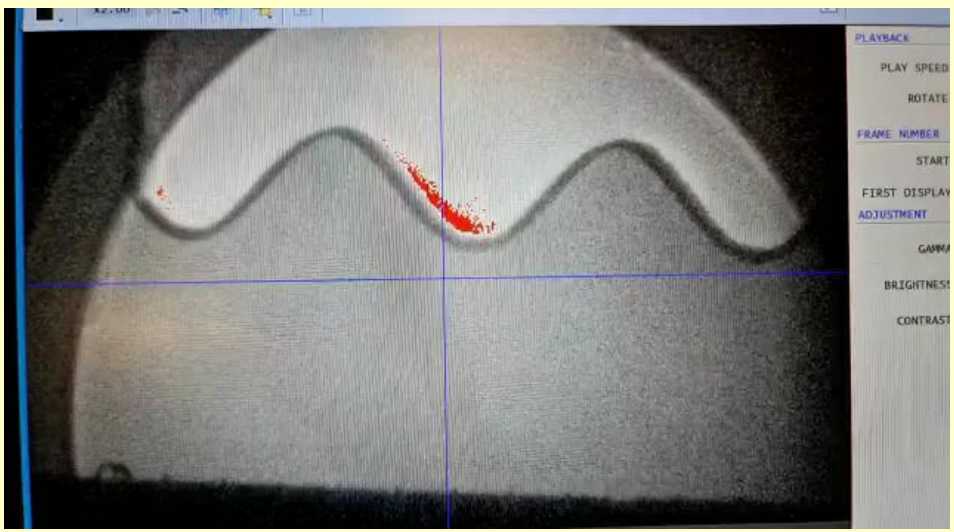
Shock front displacement in the vertical direction for planar wire explosions with Al target and shock front obtained from simulation

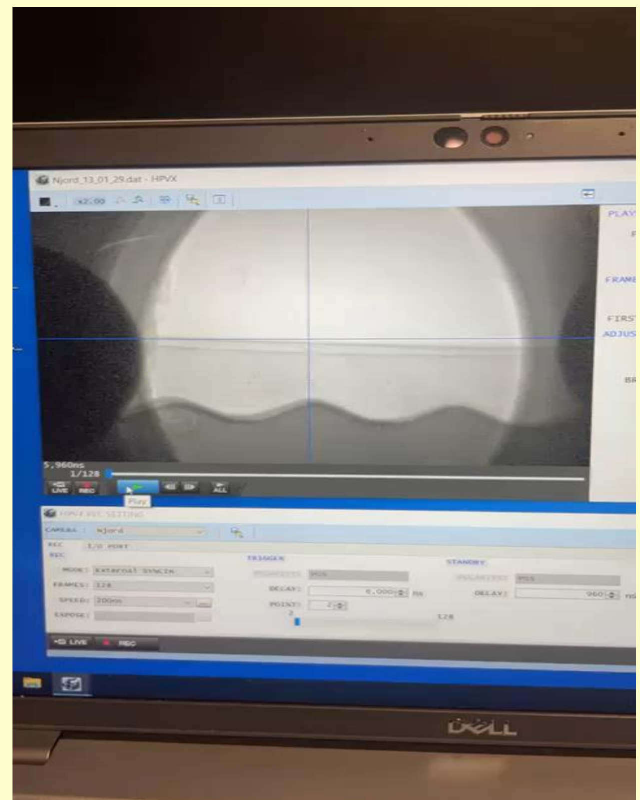


The red and blue lines represent the wire and bottom target boundary. The target distance is of 4 mm with respect to the array.


DO NOT LEAVE ME IN THE HUTCH!!!
DELL


DJUSTMENT
GAMMA:
BRIGHTNESS:
CONTRAST:
HPVX2_ID19_22_28_06.dat (150%)
5/128; 400x250 pixels; 16-bit; 24MB


PLAYBACK
PLAY SPEED
ROTATE
FRAME NUMBER
START
FIRST DISPLAY
ADJUSTMENT
GAMMA
BRIGHTNESS
CONTRAST


Njord_13_01_29.dat - HPVX
5.960ms
1/128

Thank you !