centre for fusion, space and astrophysics

THE UNIVERSITY OF WARWICK

Underwater Electrical Wire Explosion

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Outline

- Microsecond Time Scale Explosion
- Nanosecond Time Scale Explosion
- Applications
- Summary – Outline of the problems

Historic Background

Ewald Georg von Kleist 1745 - First Capacitor called Leyden Jar

E. Nairne 1774 - First exploding wire experiments

Anderson 1920 – Showed that the temperatures produced by wire explosion approach the temperatures of the sun

E. Martin 1959 – Underwater wire explosion, using electrical wire explosion for controlled initiation of underwater spark

Applications:

Light source

Shock waves source

WDM research

Opening switch - Fuse

ICF research – Z-pinch

Soft X-ray source – X-pinch (μm size, nm time)

Small Scale Wire Explosion Experiments

Generation & Characterization of WDM produced by Ohmic heating

Shunting of the Discharge in Vacuum or Gas Wire Explosions:

Large portion of the input electrical energy in vacuum wire explosion is transferred to the surrounding corona discharge created in the products of the wire surface ablation.

The best energy deposition in vacuum recently achieved by Sarkisov *et al.* was 20 times the atomization enthalpy*.

Interparticle Interaction:

Produced plasma is highly nonideal: Γ = Coloumb interaction/ Kinetic energy > 1. Large portion of the input electrical energy is transferred to the potential energy of Coulomb interaction (charge separation, ionization).

* G. S. Sarkisov, S. E. Rosenthal, K. W. Struve and D. H. McDaniel, PRL **94**, 35004 (2005).

Advantages of the Underwater Electrical Wire Explosion

Shunting of the discharge

1. High breakdown voltage of the water medium (>300 kV/cm).
2. Water's high density prevents the ablation

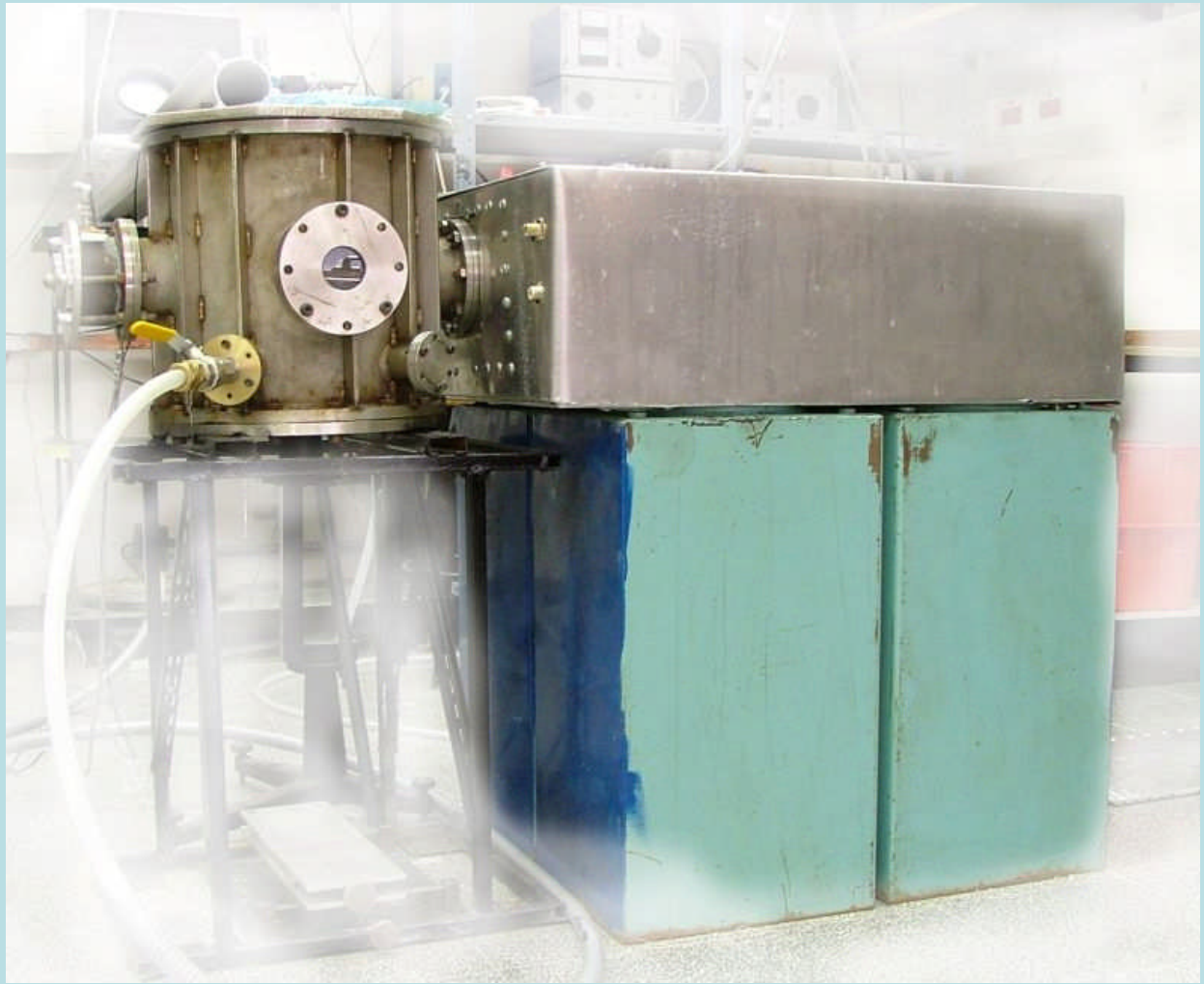
Increase of deposited energy density

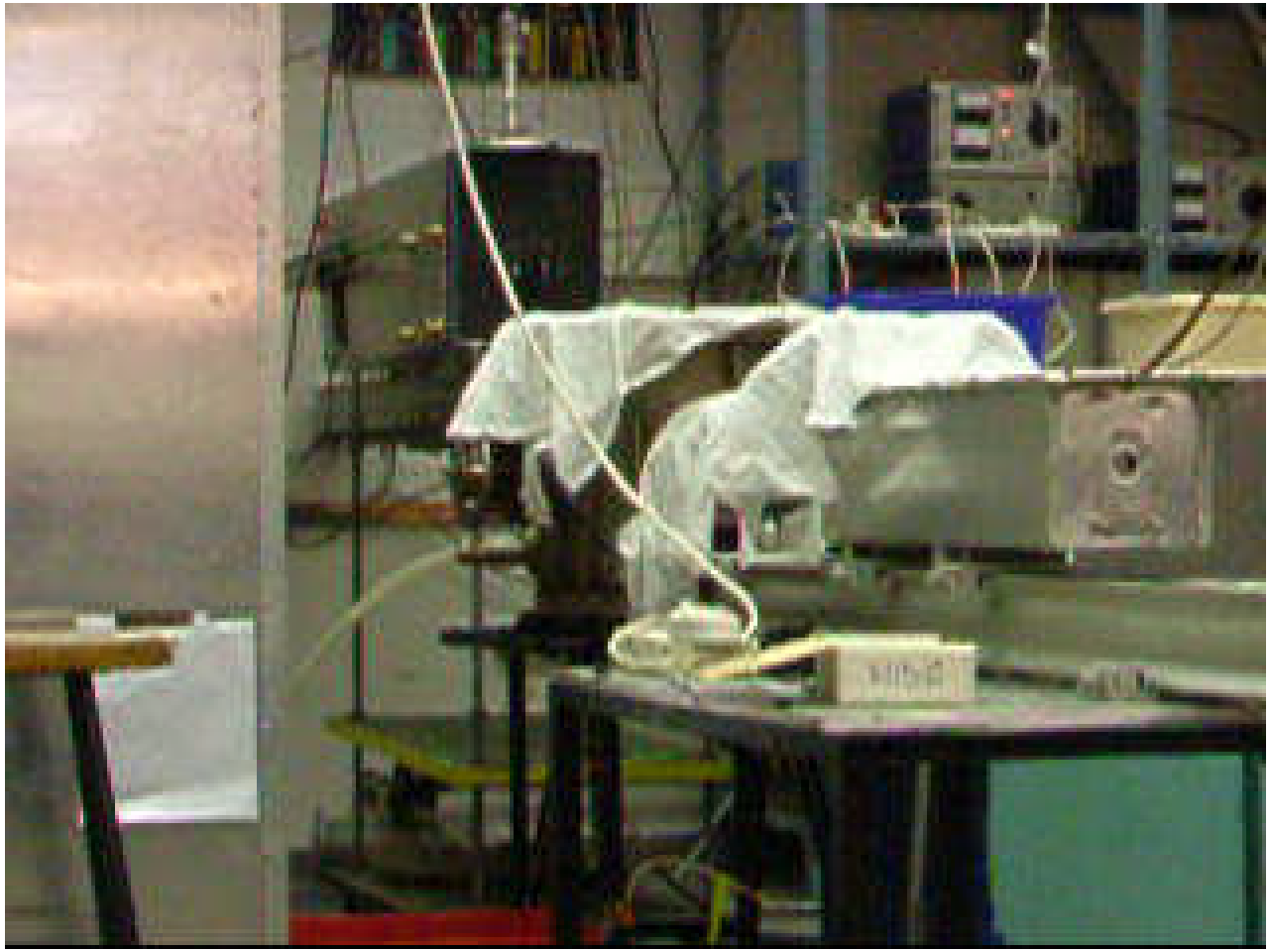
1. Incompressibility of water tempers expansion of the wire and leads to the increase in the current density.
2. Substantial decrease in the energy loss to the shunting channel.

Easy experiment

Microsecond Time Scale Explosion

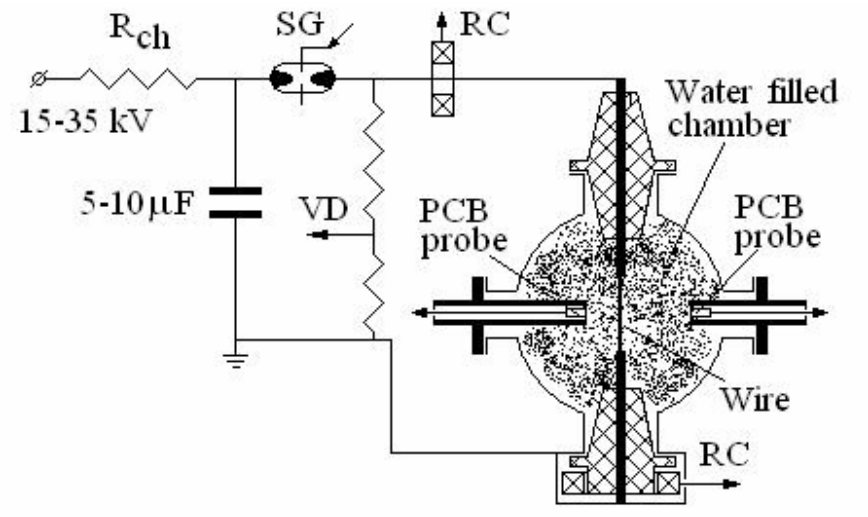
Microsecond Timescale Generator

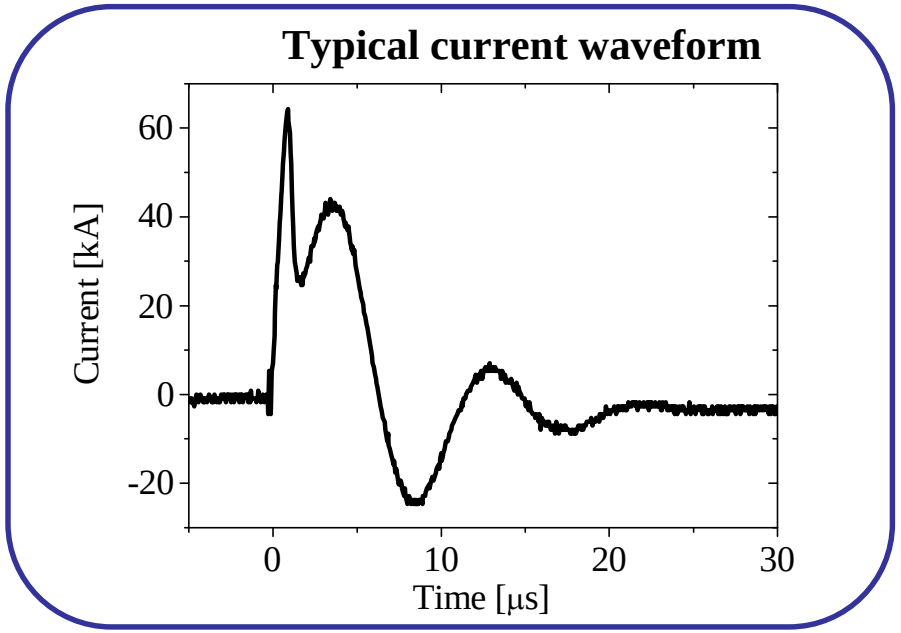




Microsecond Time Scale Explosion

Microsecond Timescale Generator





- **Stored energy: W ≤ 7 kJ;**
- **Voltage: V= 10…35 kV;**
- **Peak current: I ≤ 150 kA;**
- **Capacitance: C = 2.7…10.8 μF;**
- **Self-inductance: L=400 nH**
- **Discharge gap: D = 30…120 mm;**

$$\frac{dI}{dt} \approx 10^{10}\ A/s$$

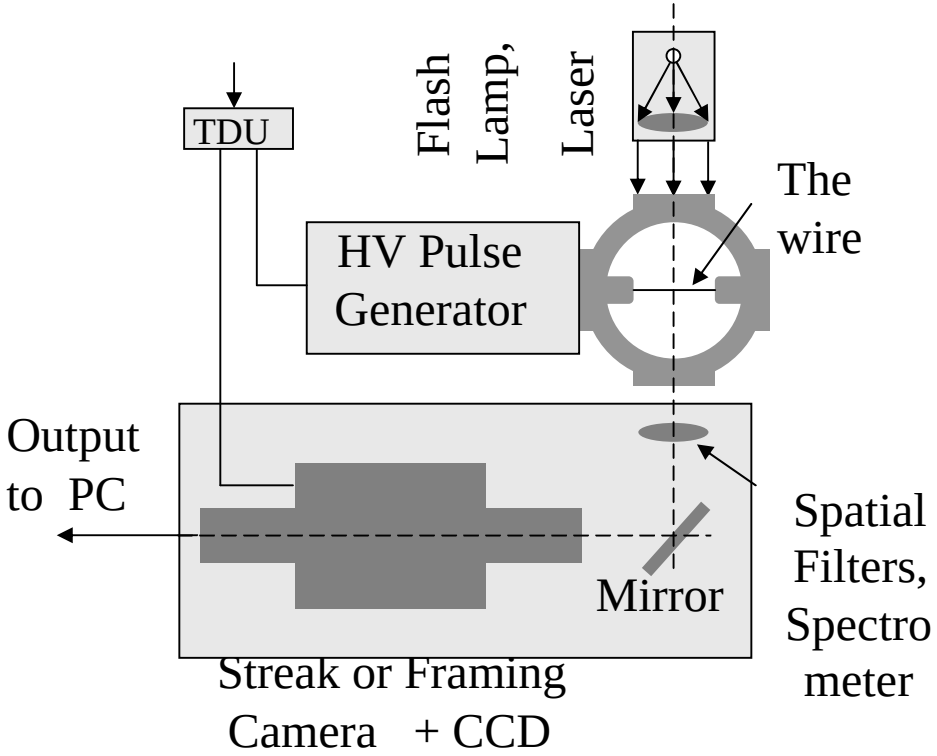
Diagnostics Tools

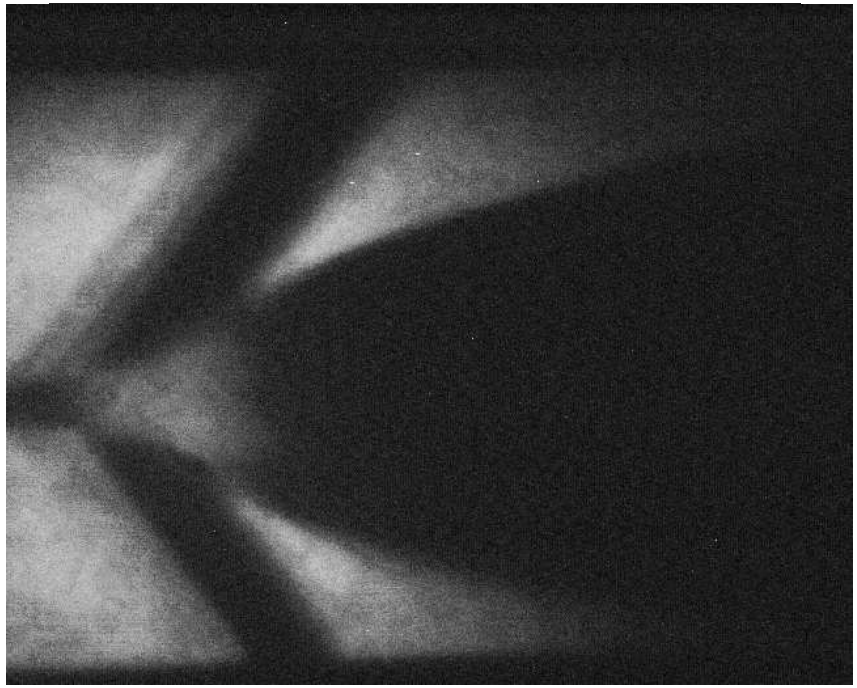
- Electrical probes: voltage & current monitors.
- Electro – mechanical pressure gauges*.
- Optical: Shadow, Schlieren & Shearing Interferometry.
- Fast streak and frame photography.
- Fast photodiodes & narrow band interference filters.
- Visible range spectroscopy.

* Grinenko, V. Tz. Gurovich, Ya. E. Krasik, A. Sayapin, S. Efimov and J. Felsteiner, *Analysis of shock wave measurements in water by a piezoelectric pressure probe*, Rev. Sci. Instr. **75,** 240 (2004).

A. Sayapin, A. Grinenko, S. Efimov, and Ya. E. Krasik, *Comparison of different methods of measurement of pressure of underwater shock waves generated by electrical discharge*, Shock Waves, s00193-06-0011-8, (2006).

Diagnostics Tools: Basic Optics Arrangement

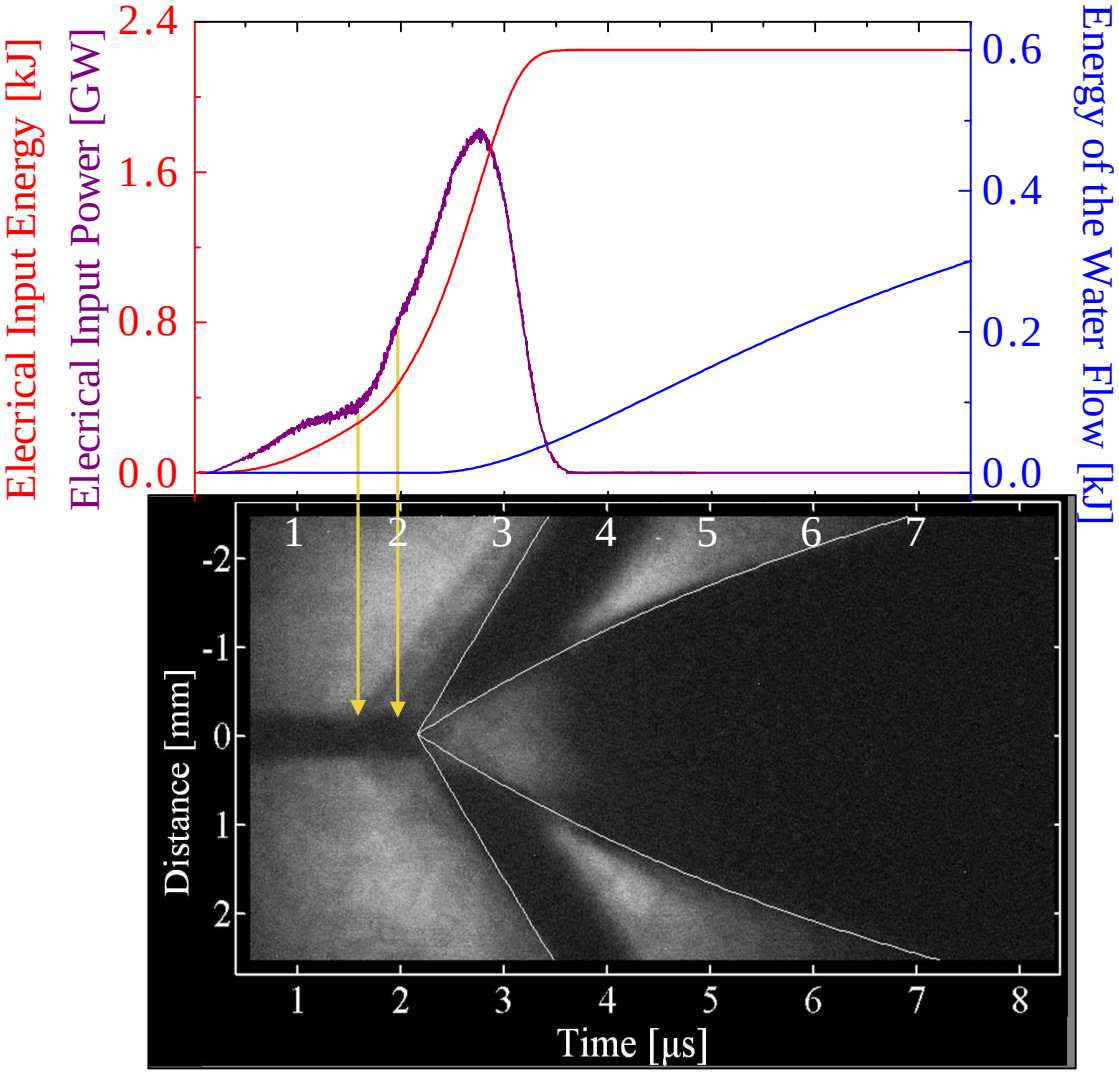




Basic Experimental Results

Cu Wire 510μm in diameter, 85mm in length, 30 kV charging voltage – Electric & Pressure analysis

Electric measurement & Hydrodynamic calculation



Maximum Estimated Pressure

Obtained in this experiment:

$P_{max} \sim 7$ kBar

Microsecond Time-Scale Explosion: Summary

- Maximal Generated SW Pressure [kBar] ~ 10
- Maximal DC Temperature [eV] ~ 1.2
- Maximal Electrical Input Power [GW] ~ 2.0
- Maximal Current Rate [A/s] ~ 10^{10}
- Maximal Energy Deposition [eV/atom] ~ 11

Related publications:

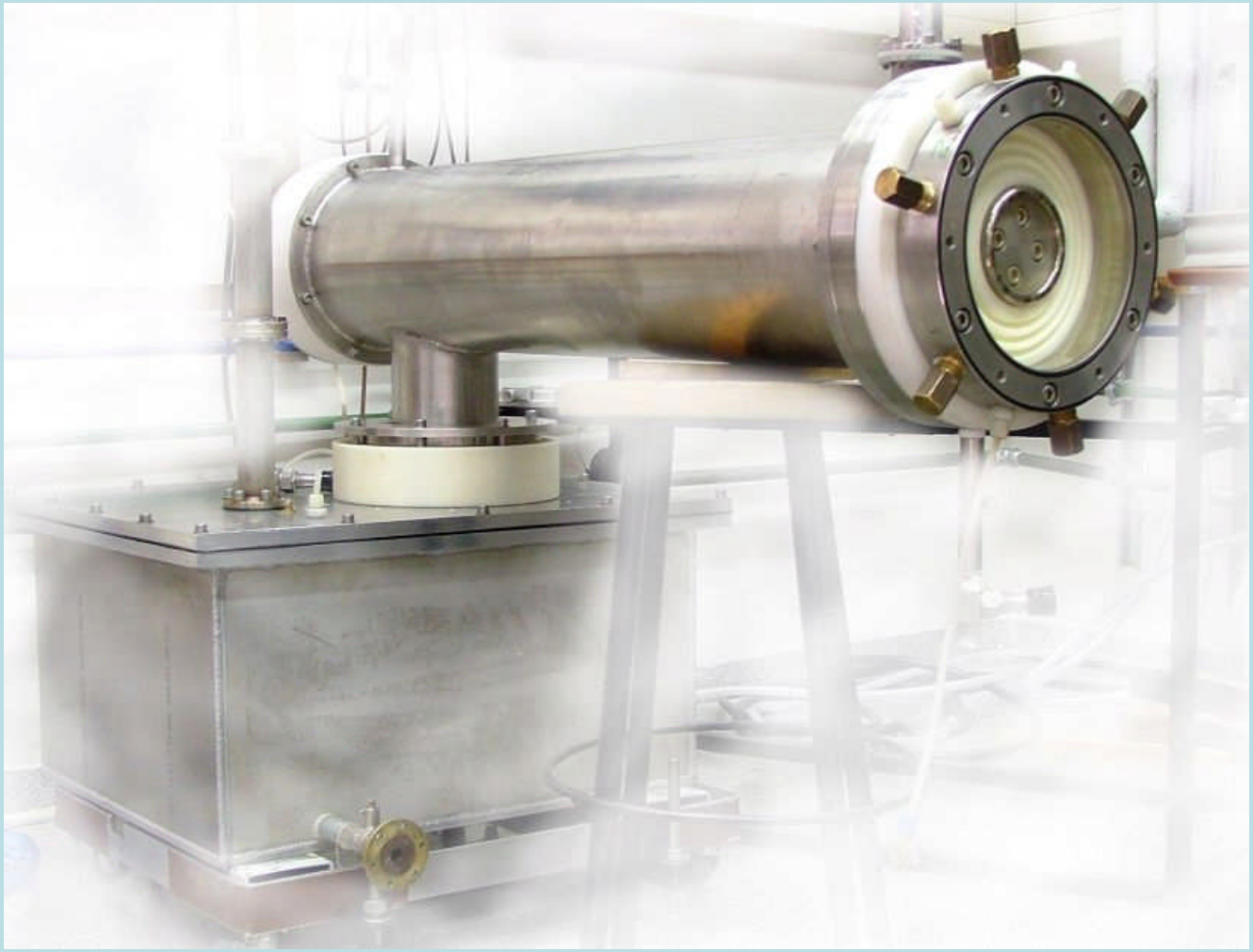
V. Ts. Gurovich, A. Grinenko, Ya. E. Krasik, and J. Felsteiner, *Simplified model of underwater electrical discharge*, Phys. Rev. E **69,** 036402 (2004).

A. Grinenko, A. Sayapin, V. Tz. Gurovich, S. Efimov, J. Felsteiner and Ya. E. Krasik, *Underwater Electrical Explosion of a Cu Wire* J. Appl. Phys. **97,** 023303, Jan. 2005.

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).

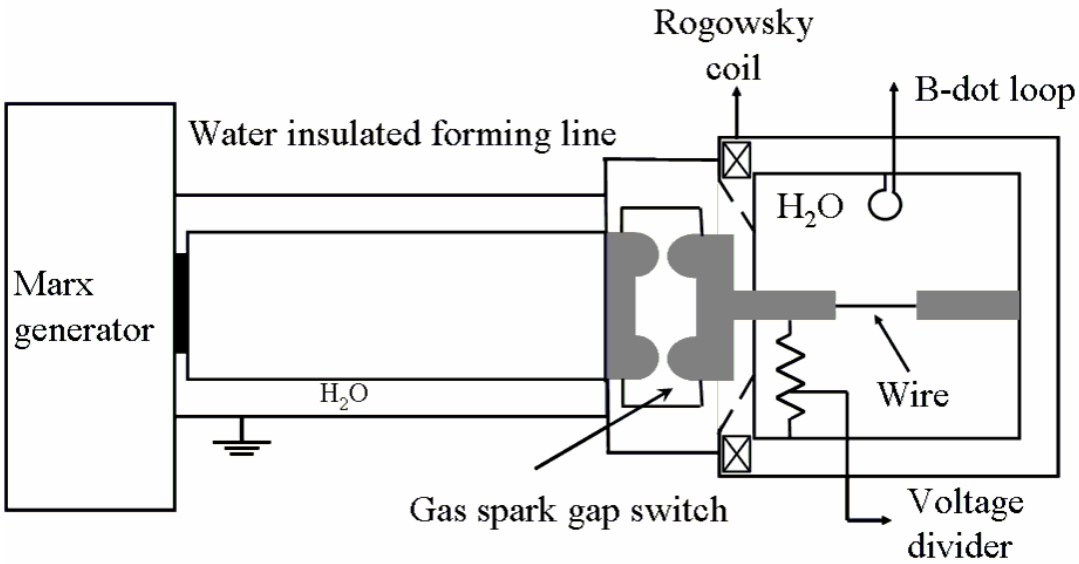
Nanosecond Time Scale Explosion

Nanosecond Timescale Generator

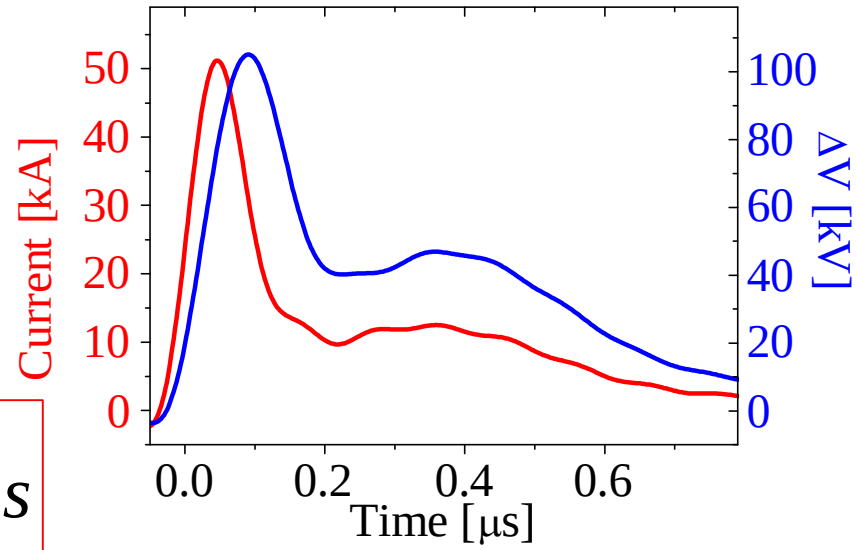


Nanosecond Time Scale Explosion

Nanosecond Timescale Generator



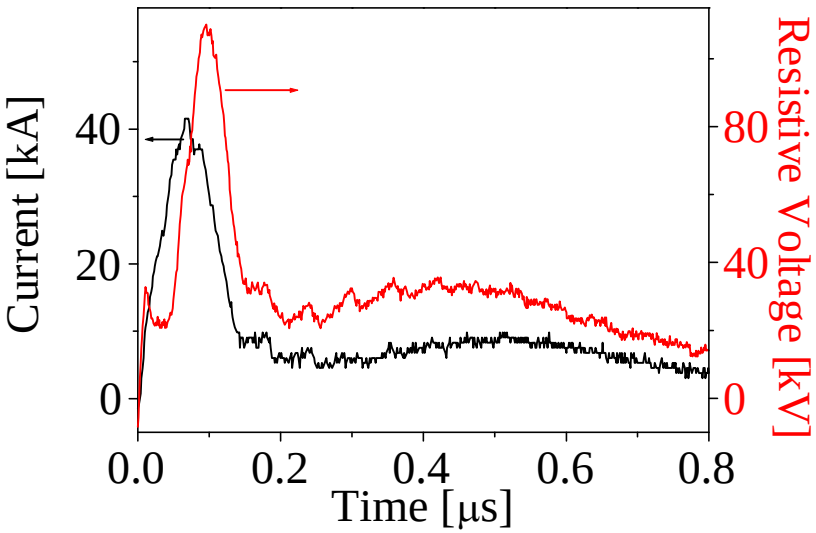
- **Stored energy:** $W_{max} = 700\text{J}$
- **Voltage:** $V_{max} = 240\text{kV}$
- **Peak current:** $I_{max} = 100\text{kA}$
- **Wave impedance** $Z_0 = 1.7\Omega$
- **Discharge gap** $D = 30 \div 150\ \text{mm}$

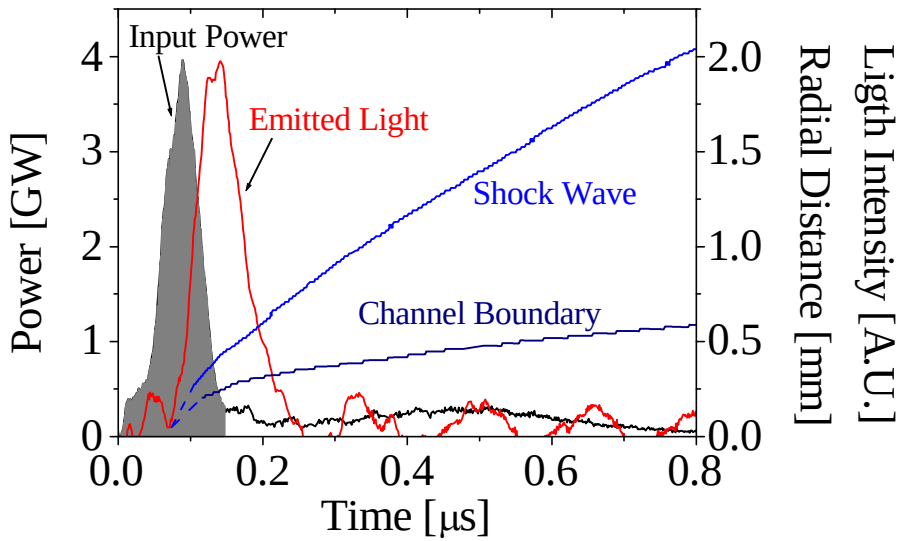


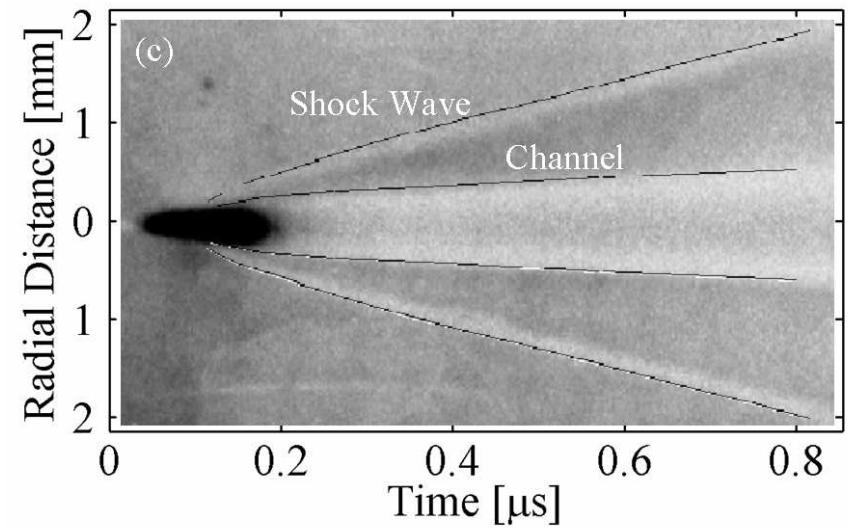
$$\frac{dI}{dt} \approx 10^{12}\ A/s$$

Basic Experimental Results

Aperiodic Discharge - Cu Wire 100μm in diameter, 100mm in length, 35 kV charging voltage







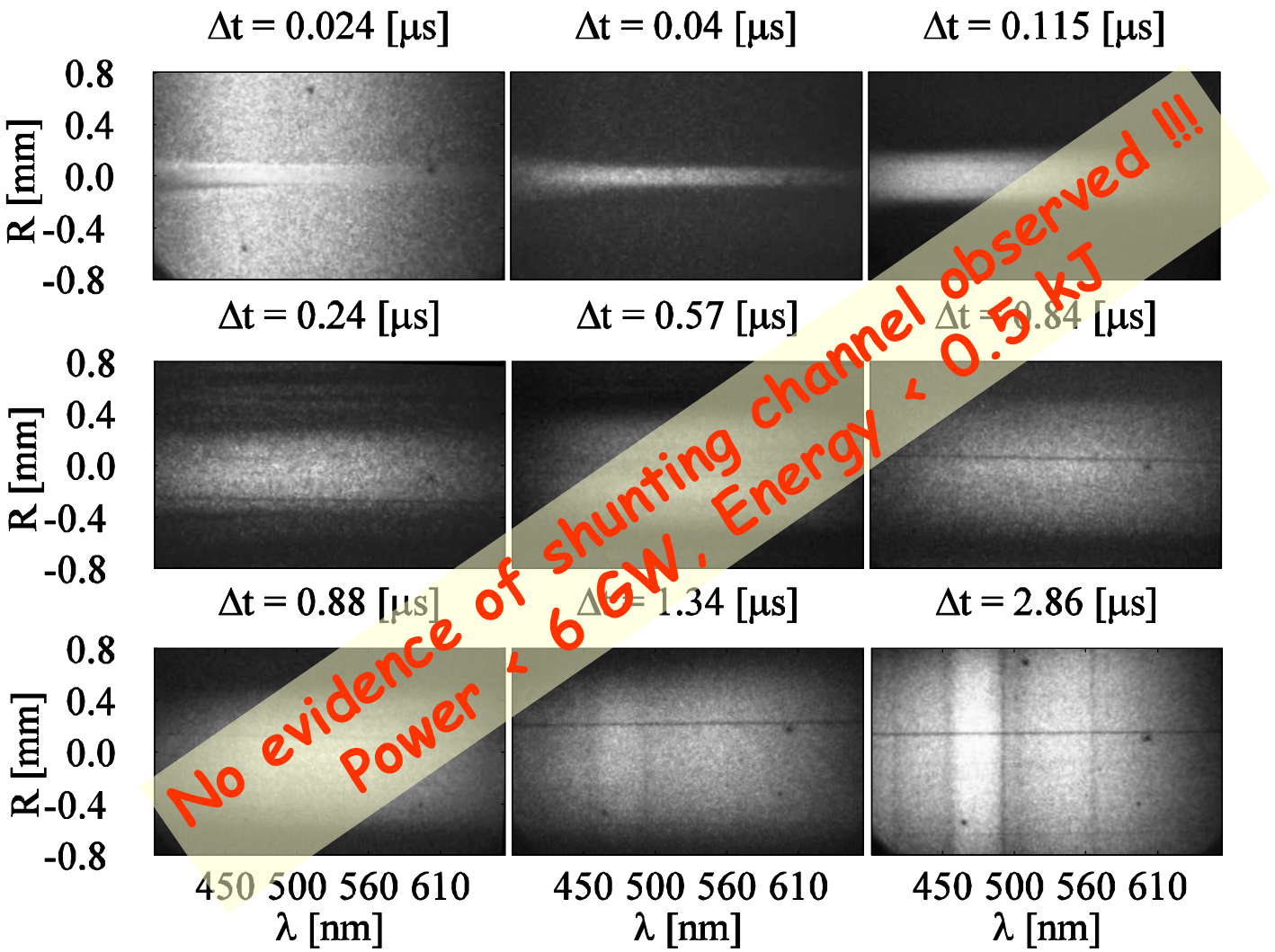
Maximum Estimated Pressure

Obtained in this experiment:

P_{max} ~ 50 kBar

Shunting Discharge Channel Observation

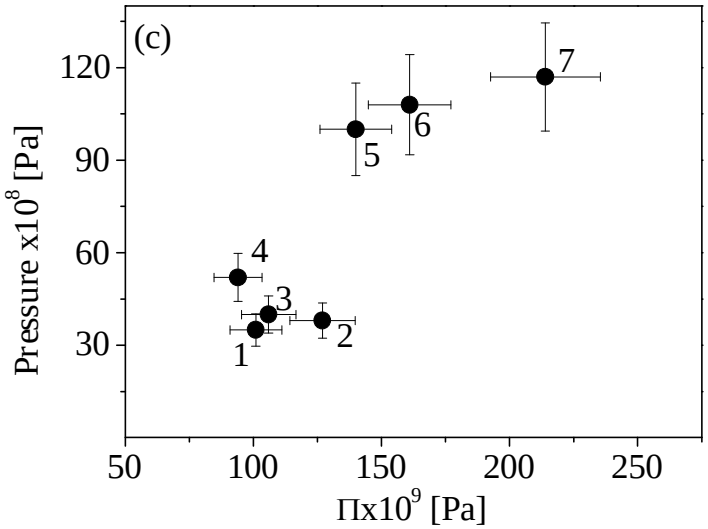
Spectrum of Cu (L = 50 mm, Ø = 100 μm) wire explosion, taken with backlight turned on.

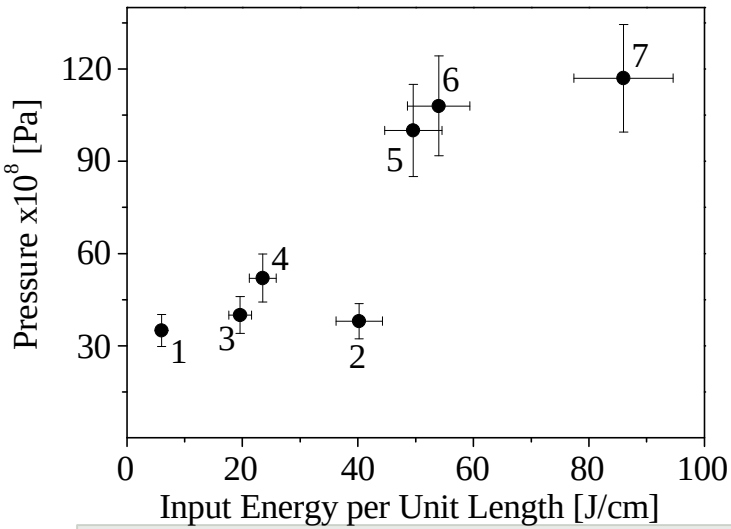


A. Grinenko, S. Efimov, A. Fedotov, and Ya. E. Krasik, *Adressing the problem of plasma shell formation around an exploding wire in water*, Physics of Plasmas 13, 052703 (2006).

Similarity Laws

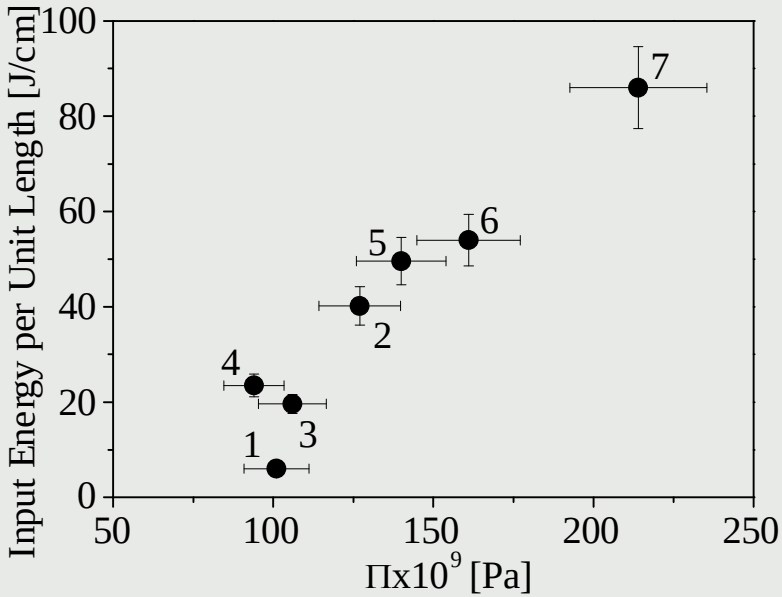
Maximal pressure at the channel boundary as a function of different discharge parameters





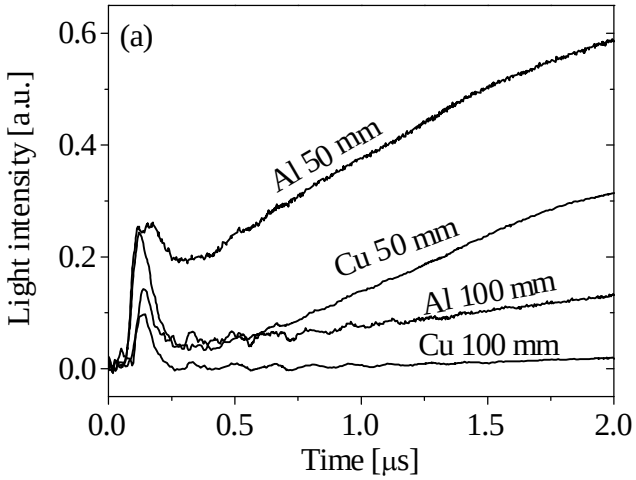
$$\Pi = \sqrt{\frac{\rho_0}{l_w}\left(\frac{dP}{dt}\right)_{\max}}$$

The dependence of the pressure *v.s.* the deposited energy and Π (power rate per unit length) suggests that the deposited energy per unit length is proportional to Π.

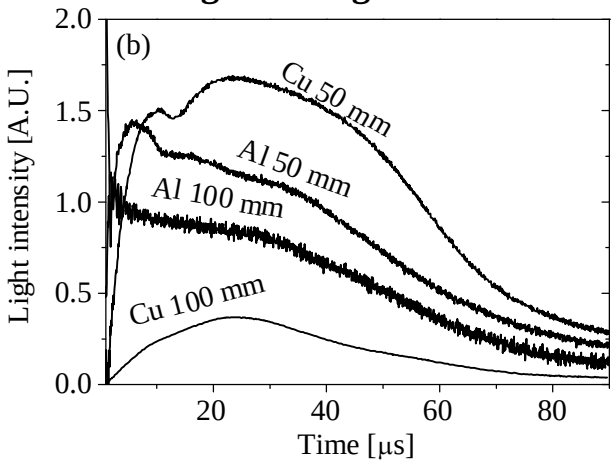


Emitted Radiation Analysis

Measured emission of white light in short time scale



Measured emission of white light in long time scale



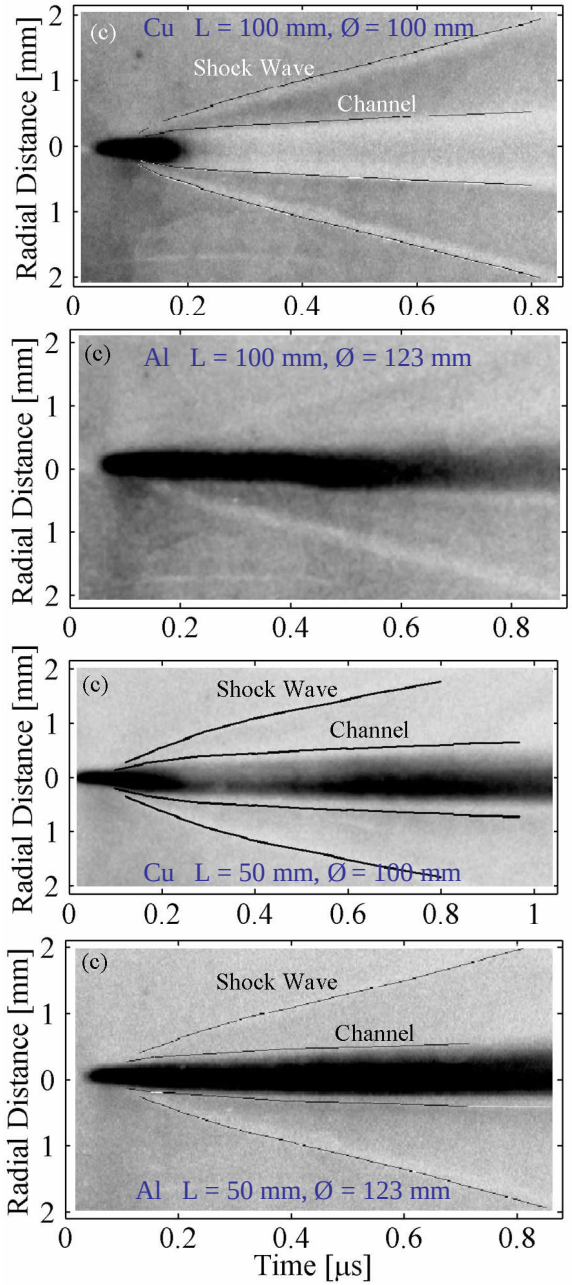
The light radiation is emitted in two pulses: short light pulse's typical duration 100-300 ns & long light pulses typical duration up to 100 μs.

Short pulse is emitted during the wire explosion - emission from the surface.

This data can be used for temperature estimation.

Long pulse is probably a result of a growth of emitting area due to creation of micro particles and their relatively long cooling.*

The estimated size of a micro particles is of the order of 0.1 μm.



*G. S. Sarkisov, P.V. Sasorov, K. W. Struve and D. H. McDaniel, J. Appl. Phys. 96, 1674 (2004).

Temperature Estimation

The measured emitted radiation has a continuum Black Body – like spectrum.

The reason: discharge channel plasma has a relatively low temperature and high density – high opacity.

Emitted light was spectrally resolved using narrowband interference filters.

Light was recorded by fast photodiodes.

Two approaches for temperature estimation were used:

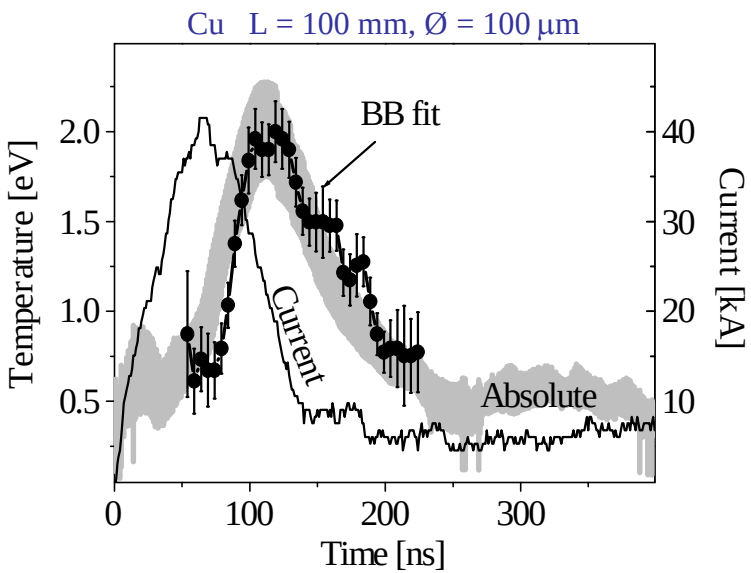
(1) Fitting of the obtained spectrum with a Planck function;

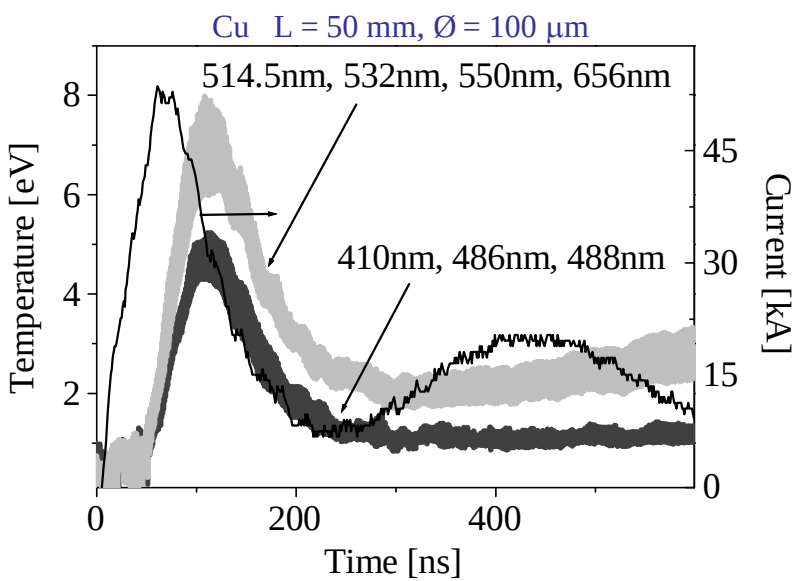
(2) Estimation from the absolute intensity of the radiation at different wavelengths.

Temperature Estimation

For long wires & low temperatures (<2 eV) the BB assumption worked well and good agreement was obtained between the two approaches (BB fit & Absolute Intensity).

For short wires & high temperatures (>3 eV) the BB assumption failed and different temperatures were estimated when using different spectral ranges.





Experiment - Summary: μsec v.s. nsec Timescale

	μsec	nsec
➢ Stored Energy [kJ]	~ 7.0	~ 0.7
➢ Current Rise Rate [A/s]	~ 10^{10}	~ 10^{12}
➢ Maximal Electrical Input Power [GW]	~ 2.0	~ 6.0
➢ Maximal Energy Deposition [eV/atom]	~ 10	~ 60
➢ Maximal Generated SW Pressure [kBar]	~ 10	~ 100
➢ Maximal DC Temperature [eV]	~ 1.0	~ 7.0

Theoretical Analysis - MHD Simulations

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

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

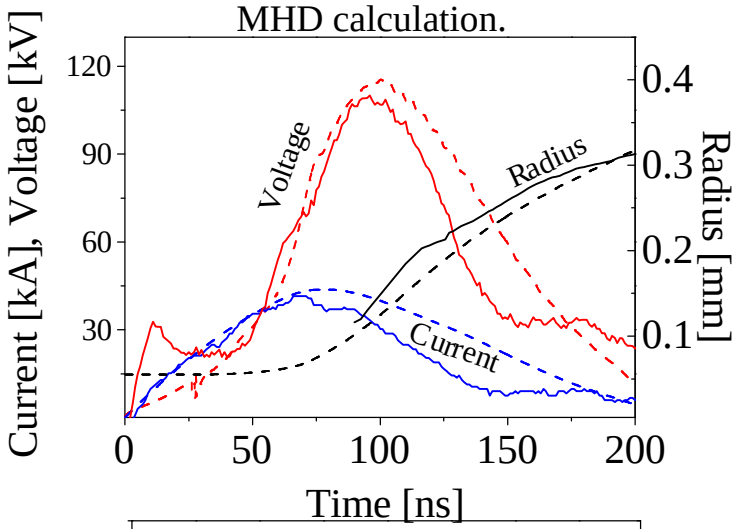
$$\sigma = \sigma(\varepsilon, \rho); \quad \kappa = \kappa(\varepsilon, \rho);$$

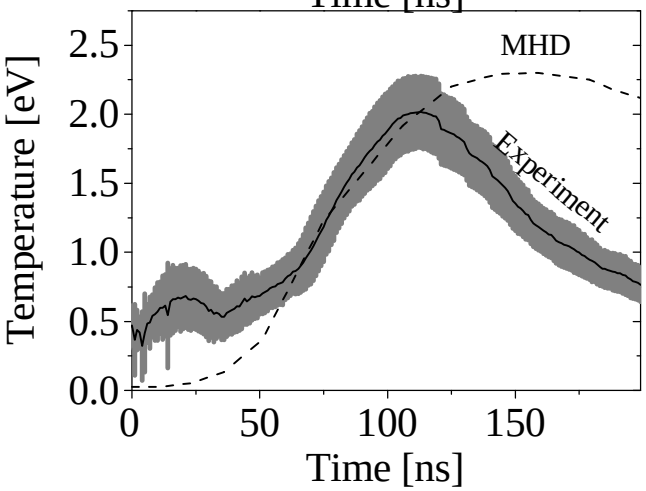
Transport parameters

MHD Calculations

Experimental & MHD calculation results of the explosion of Cu (L = 100 mm, Ø = 100 μm) wire.

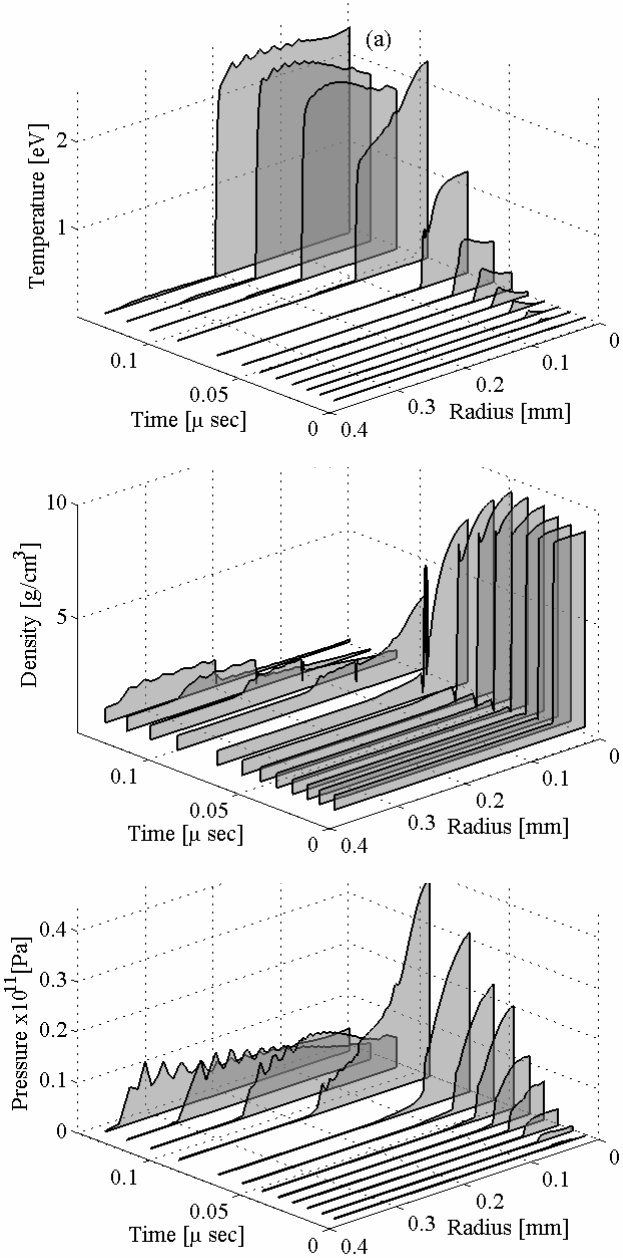
Solid curves – experimental results; Dashed curves – MHD calculation.



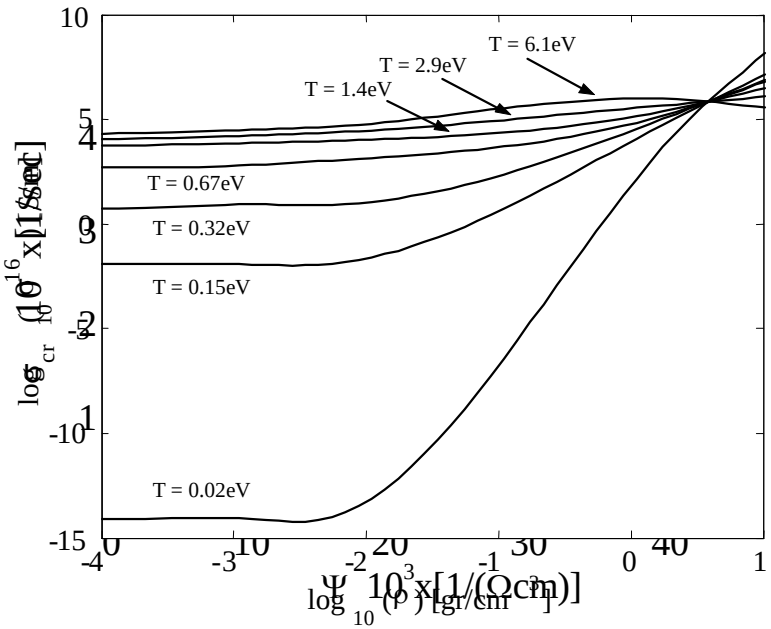


Surface discharge temperature ~ 2 eV

On axis pressure ~ 400 kBar



Transport Parameters



The semi empirical model* allows calculation of the specific conductivity. The model is applicable in the metallic and fluid phases of the material.

First, the conductivity at the normal density is calculated as:

$$\log_{10}\left(\sigma(1,T)\right)=\log_{10}\left(\sigma_0(1,T)\right)-\alpha\left[\log_{10}\left(\sigma_0(1,T)\right)-\log_{10}\left(\sigma_0(1,T_0)\right)\right]$$

Second, the conductivity in the metallic and liquid states is calculated as:

$$\ln\left(\frac{\sigma(\delta,T)}{\sigma(1,T)}\right)=\Phi(\chi,\varepsilon)\ln\left(\frac{\sigma_{cr}}{\sigma(1,T)}\right)\frac{\ln(\delta)}{\ln(\delta_{cr})}$$

$$\Phi(\chi,T)=\begin{cases}\chi-(1-\chi)\dfrac{\varepsilon}{\varepsilon_{cr}} & \text{for } \delta_{bin}\le\delta\le 1\\ 1 & \text{otherwise}\end{cases}$$

$$\chi=\frac{\ln(\delta)}{\ln\left(\delta_{bin}(T)\right)}$$

The variation of the parameter α is used to tune the delay between the calculated voltage and the current pulses to be similar to the delay which was observed in the experiments Once α is determined the value of σ_{cr} can be found such that the peak values of experimental and calculated voltage coincide. The dependence of σ_{cr} on the parameter ψ which is a combination of the discharge parameters is shown in the figure.

$$\Psi=\frac{L_w}{R_w^2}\frac{I_{\max}}{V_{\max}}\propto\frac{j_{\max}}{E_{\max}}$$

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

Summary

Diagnostics

Pressure Gauges: Require careful calibration and post measurement processing. May be used to measure spatial distribution of flow & to estimate the total mechanical energy of the SW.

Optical Methods: Accurate when SW velocity measurement is concerned. Must be combined with HD simulations in order to provide data about spatial distribution of the flow & to estimate the total mechanical energy of the SW.

Temperature: No reliable temperature diagnostic suitable for experiment was found. Conventional spectroscopy doesn't work due to absence of line spectrum. Continuum radiation strongly deviates from Black Body.

Modelling

EOS – different equations of state of metals exist that agree to some extent. However transport parameters associated with them are not as much developed.

Fast explosion – Multi phase material might be created, phase transition must be better understood and modelled.