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A Supersonic Underwater Discharge as a High-Power Ultrasound Source

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Abstract—A supersonic underwater discharge system, driven by a pulsed power generator with 235 ns voltage rise time was developed to be used as a powerful ultrasound source. The paper presents details of the system's components and the various diagnostic methods used, together with the main findings obtained during the first experimental campaign. The system generated a peak pressure of 184 kPa at 1 m distance, with an efficiency of energy conversion from electrical to acoustic estimated as 0.8%. The pressure profile was found to display a resemblance to the radiation pattern generated by a dipole antenna. Using an ultrahigh speed camera, a study of the inter-electrode discharge revealed details of the pre-breakdown streamer dynamics and an estimate for the lifetime of the post-breakdown plasma column. The way forward includes testing the system at a very high repetition rate.

Index Terms— Ultrasound, pulsed power, plasma, streamer, pulsed pressure

I. INTRODUCTION

HIGH-power underwater electric discharges have been fundamental to pulsed power technology for decades. Namely in pulsed power switching, but also in a large number of industrial applications including: underwater welding and electro-hydraulic forming [1], shockwave generation for industrial sludge treatment, removal of foreign deposits from pipe walls or materials fragmentation, separation, reduction and recycling [2-4], for mining applications such as blasting [5] and drilling [6], for demolition [6], wastewater treatment and sterilization [7], bio-fouling control [8], removal of algae [9], as well as special bio-medical applications. A number of these applications are well described in a book dedicated to the pulsed electric breakdown of liquid phenomena [10].

The present paper is related to using electrical discharges to produce high power acoustic waves with large amplitudes, short duration and wideband frequency. Such acoustic waves, termed high-power ultrasound (HPU) [11], have often been used in maritime applications [12-13]. There are two main regimes by which HPU can be generated: *subsonic* (by oscillating bubble-based mechanism) and *supersonic* (by streamer-based mechanism).

The subsonic technique is achieved by a relatively slow (tens of microseconds) application of a high-voltage across electrodes immersed in water, resulting in a Joule-heated creation of a gas bubble within which electrical breakdown of

the water gap occurs. The discharge-driven periodic expansion and collapse of the bubble produces HPU by virtue of the bubble's surface performing the role of the membrane in a loudspeaker. A single discharge may produce several oscillations over hundreds of microseconds, up to tens of milliseconds, depending on the water conductivity and the electric field strength applied. Recently, more attention has been given to understanding the physics of subsonic HPU sources [13-17]. Owing to the long discharge period it is not practical to achieve a high pulse repetition frequency (PRF) operation with subsonic discharges.

By contrast, the supersonic technique requires a very fast voltage impulse, with a rise time of tens to hundreds of nanoseconds. This impulse is normally applied to an electrode geometry specifically designed to generate an intense and highly inhomogeneous electric field distribution, such as point-plane. Key processes involved in the supersonic electric breakdown of water are thus facilitated: field emission and field ionization, field acceleration and impact ionization. Through a combination of these processes, conducting ionization paths known as *streamers* propagate across the electrode gap with a tree-like structure. Upon the successful connection of the electrodes by an ionized path, current is mainly directed through it, forming a highly conductive plasma channel. The corresponding Joule energy is delivered to the surrounding water, causing the water to violently expand and generate a powerful shock wave.

The HPU generated under these circumstances is different from that produced with the bubble-based subsonic technique, as the energy is deposited much more rapidly, resulting in a much shorter duration (microseconds) acoustic pulse with a considerably wider bandwidth (up to a few MHz).

The literature surrounding supersonic pre-breakdown (streamer) phenomena has been comprehensively reviewed in [18] and the physics of the fast breakdown process in [19-20]. However, the application of these processes to generate HPU remains an unexplored field, to the best of the authors' knowledge.

The present paper is dedicated to the development of a supersonic HPU source using a bespoke pulsed power generator. The major interest in developing this type of source is the unique capability to drive this low-energy system at very high PRF. There are applications in the bio-medical domain

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Fig. 1. Equivalent electric scheme of the HPU system based on a fast-pulsed power generator. See text for details.

[21-22], food processing technology [23] and geological survey that require a HPU source with such characteristics. The system described, although only demonstrated in single-shot mode in the present work, was therefore designed specifically for future 1 kHz PRF operation.

The structure of the paper is presented below. Section 2 describes the pulsed power generator, the electrodes, and the practical arrangement in a laboratory water tank. Diagnostic instrumentation, and a technique for the synchronization of their outputs are also presented in detail. Section 3 presents the main findings, and section 4 comprises the conclusions along with a plan for future development.

II. PRACTICAL ARRANGEMENT

A. Pulsed power generator

The main requirements for the design of the pulsed power generator were to produce a 100 kV output and to operate at a PRF of 1 kHz. In a preliminary phase of this research a Tesla transformer-based generator, using a closing switch based on a corona stabilized closing switch was successfully tested up to 1 kHz PRF [24].

The present work is based on an improved HPU system, with the electrical scheme of this faster 235 ns rise-time generator presented in Fig. 1. A low-inductance capacitor type 37331 (General Atomics [25]) capable of operating at 1 kHz PRF and having a capacitance $C_1 = 153$ nF is mounted in the primary winding circuit of a magnetic core transformer. For single-shot operation, the closing switch (S_1 in Fig. 1) is a trigatron type SG-101M-75C (R. E. Beverly III & Associates [26]), triggered with a trigger head pulse transformer type THD-02B-02. The pulse transformer is controlled by a trigger generator type PG-103D4-02a via a 20-m fiber optic isolation link. For single-shot operation at a charging voltage of $V_0 = 12$ kV, the trigatron operates pressurized with 1 bar pressure N_2 . In these conditions and including all components, the primary winding circuit has a total equivalent resistance of $R_b = 122$ m Ω and a leakage self-inductance of $L_b = 200$ nH. The transformer, which will be described in detail elsewhere [27], has a turn ratio of 1:12 with a single-turn primary winding made from thin copper strip having a self-inductance $L_1 = 5$ μ H and a secondary winding of 12 turns made from a round copper conductor 2 mm in diameter mounted on a conically shaped coil former and having a self-inductance $L_2 = 709$ μ H. The transformer core is made from Metglas® type AMCC367S [28], which achieves a magnetic

coupling coefficient of $k = 0.99$. The transformer is mounted inside a small-size plastic oil tank together with the HV capacitive load $C_2 = 1.1$ nF containing 16 identical TDK UHV-3A 4 nF/20 kV ceramic capacitors mounted as two parallel connected stacks, each stack having eight series connected 4 nF units. The total equivalent resistance of the secondary winding circuit is $R_s = 10$ Ω , with the total leakage self-inductance being $L_s = 0.8$ μ H.

B. Underwater discharge electrodes and their ancillary equipment

The discharge electrodes are formed of a pin-plane pair, with the plane taking the form of a hemisphere, 60 mm in diameter, the cylindrical-conical pin having an outer diameter of 5.8 mm and a tip radius of about 500 μ m. For high PRF testing, the electrodes will be manufactured from copper or sintered Cu-W. However, for convenience, in the single-shot experiments reported here the hemisphere was made from brass and the pin electrodes from stainless steel. The electrodes were coaxially mounted at an adjustable distance inside a watertight acrylic tube filled with deionized water. It was experimentally demonstrated that, for minimizing the Joule losses during the pre-breakdown phase, the electrodes must be covered as much as possible with an insulating material to increase the underwater assembly total equivalent resistance. This requirement proved to be difficult to implement in practice. During the preliminary phase of this research, the most significant issues observed after operating with long bursts at a high PRF were (see Fig. 2) were:

- unwanted electric breakdown at the insulator-metal-water triple point
- destruction of insulators caused by strong shock waves

The design of the pin electrode used for the single-shot operation during this stage of the research features a threaded head, which allows for interchanging the electrode to investigate alternative geometries and replacing a damaged head without disassembly of the entire electrode support system. It does however leave a small metallic area uncovered at the interface between the electrode and its support. For increasing the efficiency while operating the system using freshwater, this area had to be covered.

The solution to minimize damage to the hemisphere electrode insulation was to cover less of its surface (in close proximity to the plasma discharge) with epoxy resin, while also implementing a small angle between the insulator and the metal, to tackle the triple point field enhancement.

Fig. 2. Extent of damage caused to electrode insulation by shock waves and intense electric fields: a) hemisphere electrode with cracks, b) pin electrode with deposits due to chemical reaction near triple point and shock wave damage.

Fig. 3. Electrodes successfully used during the present work. a) hemisphere electrode b) pin electrode

Fig. 4. The electric field distribution produced by the pair of electrodes presented in Fig. 3, when mounted 4 mm apart. The prediction is made using the CST software [29]: for 1 V applied on the pin electrode, a peak field of 1000 V/m is generated.

Fig. 3 show the pair of electrodes used in the present work and Fig. 4 presents the electric field distribution predicted by the CST software [29]: for 1 V applied to the pin for an inter-electrode gap of 4 mm, the peak field generated under these circumstances reaches 10 V/cm.

For the purpose of connecting the electrodes to the generator via a (several meter) long transmission line, a HV 50 coaxial cable was not suitable as its characteristic capacitance (about 100 pF/m) would introduce a capacitance into the circuit comparable to C_2 . Therefore, two flexible HV cables were used: the core of a 150 kV coaxial cable type 212A [30] connecting the pin electrode to the HV terminal and a 40 kV cable type 167-9180 [31], connecting the hemisphere to ground. Tests performed during the preliminary phase of this research demonstrated that for most efficient operation of the HPU source, *the pin should be positively charged*. Fig. 5 presents the experimental arrangement used for testing the HPU source, with an acrylic tube assembly containing the electrodes and filled with deionized water immersed for testing into the 1.5 m³ plastic water tank with dimensions (x,y,z) 1.25 m x 1.68 m x 0.8 m.

During the present preliminary testing, many hundreds of shots were fired in single-shot mode. Some erosion to the electrodes was observed, but at 4 mm electrode separation this did not affect the reliability of discharge.

C. Diagnostics

1) Electrical

- i) *Voltage*: two voltage probes were used (VP in Fig. 1).

Fig. 5. Experimental arrangement at the water tank (not to scale). a) x-z plane view b) x-y plane view. See text for details.

VP₀ is a type PVM-1 probe [32] used for DC measurements, while VP_s is a type PVM-100 probe, capable of measuring a peak of 150 kV with 90 MHz bandwidth [32].

- ii) *Current*: two current transformers (CT in Fig 1) type 2877 [33] (peak current 100 A, bandwidth 200 MHz) were installed as a pair, to provide both a positive and a negative output, allowing for the identification and removal of unwanted capacitive coupling. As the peak plasma current can reach values in excess of 1 kA, this exceeds the capability of the above-mentioned transducer. In order to safely use the current transducers, the HV cable attached to ground was connected to an assembly made of 12 short, parallel, connected wires and the two current probes were installed on a single wire, thus each measuring about 1/12 of the total current. As the currents are not exactly evenly distributed through the 12 wires, the output of these probes was separately calibrated using two, lower frequency bandwidth, type 410 current monitors [33], mounted directly on the HV cable attached to ground.

- iii) dl/dt : a simple magnetic pick-up probe, calibrated as an I-dot probe (see Fig. 1), was mounted inside a small helical coil made from the HV cable attached to ground.
- iv) *Voltage across electrodes*: the VP_S probe measures the voltage across C_2 , which can be written as:

$$= \text{---} + \quad (1)$$

where L_t is the self-inductance of the HV transmission line, R_L is the *time dependent* equivalent resistance of the load and I_L is the current flowing through the load circuit. During an experiment R_L varies with many orders of magnitude while the voltage V_L across the electrodes:

$$= \quad (2)$$

is important for calculating the Joule energy. As VP_S , I_L and --- are all measured by specific probes, the instantaneous power P_L absorbed by the load can be easily obtained if L_t is known:

$$= \text{---} = \text{---} - \text{---} \quad (3)$$

Time integration of this power provides the energy W_L absorbed by load at a time t :

$$(\text{---}) = \int_0^t (\text{---}) \quad (4)$$

The precise value of L_t was obtained using Eq. (1) in experiments with a mock-up HV transmission line having the same topology as the real transmission line and connected to a 34 Ω HV resistor that replaced the time-varying load resistance R_L . For the arrangement used in the present work L_t was found to be 9.5 μH .

2) Acoustical

- i) *Low frequency hydrophone*: Teledyne Reson type TC4034 [34], having a usable frequency range from 1 Hz to 480 kHz. The spherical active region of the TC4034 piezoelectric hydrophone is aligned with the center of the electrode gap, in the x and z directions, with a separation of 1 m in the y direction (Fig. 5). This hydrophone is omnidirectional across its bandwidth.
- ii) *High frequency hydrophone*: Precision Acoustics type NH2000 [35], suitable for measurements in the frequency range from 100 kHz to 10 MHz. The NH2000 2 mm needle PVDF hydrophone is highly directional, particularly for high frequencies, and so great care was taken during its alignment. The active part of this hydrophone, at the tip, was mounted at a separation of 1 m from the electrode gap (Fig. 5).
- iii) *Details of hydrophone mounting and operation*
The two hydrophones were mounted using supports (see Fig. 5b) and placed at the minimum separation from one another that allowed for the full pressure wave to be captured by each hydrophone before the reflection from the other would be detected and influence the signal. The minimum separation was calculated to be 3.5 cm, and a 4 cm separation was used. The hydrophones were also separated from the tank walls and surface of the water sufficiently to prevent reflections from these surfaces from interfering with the direct pressure wave received from the HPU. Both hydrophones displayed a strong sensitivity to the powerful electromagnetic noise

generated by the pulsed power generator. Due to the conductivity of water, it was not possible to implement proper cable shielding. However, by placing battery-powered oscilloscopes inside Faraday chambers, it was possible to reduce the interference, the hydrophone upset and the recovery time following a strong electromagnetic disturbance.

- iv) *Software and data analysis*: A Mathcad [36] program was developed to analyze the data obtained from the two hydrophones. To help with alignment of the highly directional NH2000 hydrophone, the software was used to test agreement with the TC4034 signal in the overlapping receiving bandwidth (i.e., 100 kHz to 480 kHz). As neither hydrophone was individually capable to cover the ultrawide spectrum generated by the HPU, the software was used to perform the FFT of the pressure signals and then trim and stitch the two signals in the frequency domain, before performing the inverse FFT to obtain the pressure signal in the time domain corresponding to the entire bandwidth.

3. Optical

An ANDOR sCMOS iStar ultra-fast camera [37] was operated with a 3 ns exposure and increased microchannel plate (MCP) gain, to allow for clear images to be obtained. When longer exposure times were used, the very fast motion of the streamers resulted in blurred images. A NIKON Sigma 150mm f/2.8 APO Macro EX DG camera lens was coupled to a number of extension tubes (Fotga Auto Focus Macro Extension Tube) to enlarge the image falling on the camera sensor (see Fig. 5a). To protect the camera against electromagnetic interference, it was housed inside a dedicated Faraday chamber, suspended above the water tank. A chamber extension with an optical window lid allowed underwater operation, thus minimizing the distance between the camera lens and the HPU source (Fig. 5a).

4) Synchronization

The complete synchronization scheme, which only includes the fast electrical and optical diagnostics, is presented in Fig. 6, where the ‘Closing switch S1’ is switch S_1 in Fig. 1 and the ‘D-dot’ is a differential electric field sensor measuring the level of electromagnetic ‘noise’ and also used for triggering and synchronization purposes.

The camera was operated in the External trigger mode with a Pre-trigger option. In this mode two input signals are needed: the first one is applied at t_0 as a Pre-trigger, preparing the camera sensor, while the second is applied at t_2 as an External trigger that (after a short time delay) activates the image intensifier to acquire a photo. The spark-gap triggering system is activated at a time t_1 , with $t_0 < t_1 < t_2$, see Fig. 6.

Fig. 6. Schematic of the synchronization scheme.

III. EXPERIMENTAL RESULTS

A. Influence of the inter-electrode gap on the peak pressure generated by the HPU source

The tests reported here were performed with water at a temperature between 20 °C and 22 °C. The results of a study to find the optimum inter-electrode gap to generate the maximum peak pressure with the present single-shot system are presented in Fig. 7. As the gap increases, the relative peak pressure increases from 84%, corresponding to a gap of 3.1 mm, to 95% for a 4 mm gap and finally to 100% for a gap of 5 mm. The corresponding breakdown voltage is presented in Fig. 8. As the gap increases from 3.1 mm to 5 mm, the breakdown voltage increases from 92 kV, to a value very close to 100 kV. Although the 5 mm gap is apparently the best separation for maximizing pressure, in practice 30% of shots were unsuccessful ('misfire'), with no voltage breakdown and no substantial pressure generated. For the 4 mm gap, the experimentally determined chance of misfire was only about 1%, while for the 3.1 mm gap there were no misfires. All shots presented in this work were performed with a 4 mm gap.

B. The characteristic pressure pattern generated by the HPU source

The results of a study to determine the pressure pattern generated at (about) 1 m distance by the HPU source is presented in Fig. 9, where polar coordinates are used with the maximum corresponding to a peak pressure of 184 kPa. Due to reflections by the dome electrode, the pressure pattern has lobes similar to the electromagnetic pattern lobes generated by a dipole antenna.

Fig. 7. The variation of the relative peak pressure with electrode gap.

Fig. 8. The time varying voltage corresponding to various inter-electrode gaps (numbers shown in mm). To display each breakdown clearly, an artificial delay was introduced between the voltage signals.

C. Data from a typical shot

The *electrical data* from a typical shot is presented in Fig. 10. The *pre-breakdown phase* in Fig. 10a, represents the time from the beginning of the discharge at $t=0$ ns (closure of S_1 in Fig. 1) up to the moment the breakdown takes place at $t=330$ ns. During this phase, while the voltage increases to its peak, an extremely small *displacement current* flows through the water, closing the load circuit. This is due to the fact that the rise time (10% to 90%) of the voltage impulse is only 235 ns, while the relaxation time of the deionised water is *much larger* i.e., $\epsilon_0 / \epsilon_w = 3.54$, where ϵ_0 is the permittivity of free space, $\epsilon_w=80$ is the permittivity of water at 20 °C and $\sigma_w=2$ $\mu\text{S}/\text{cm}$ is the conductivity of the deionised water used in the tests.

The time variation of the Joule energy absorbed by the source is shown in Fig. 11, with the final energy converging to $W_L^{\text{max}}=7.4$ J. This energy is larger than the 5 J stored in C_2 (of Fig. 1) when charged to 100 kV, showing that even after the breakdown, energy from the primary circuit continues to be pumped into the secondary load circuit.

The *optical data* in Fig. 12 represents a collection of photos taken from a number of ‘identical’ (i.e., having the same initial conditions) shots. To easily correlate the streamer dynamics with the electrical data, the time at which each photo was acquired in relation to the electrical signals of Fig. 10 is clearly indicated by letters *a-o*. It is interesting to note the various stages such as: streamer formation and dynamics during the pre-breakdown phase, the generation of the luminous central plasma column at breakdown, the slow decay of the streamers and the even slower decay of the plasma column. The first light (Fig. 12b) is detected around 140 ns, when the voltage applied on the pin electrode is 28.5 kV (Fig. 10a). Using the data of Fig. 4c, the corresponding peak electric field is estimated as 285 kV/cm. The electric breakdown at 330 ns (Fig. 12g) corresponds to 100 kV applied on the pin and a peak electric field of 1 MV/cm.

Fig. 13 presents typical rough *acoustical signals* recorded with the hydrophones positioned at 1.076 m distance from the

HPU source and at 340 degrees (or -20 degrees), as indicated in Fig. 9. Using the data analysis presented above, the resultant pressure pulse and its corresponding FFT are presented in Figs. 14 and 15, respectively. The maximum pressure recorded was 184 kPa (225 dB re 1 $\mu\text{Pa}/\text{V}$).

Fig. 10. Voltage and current signals during a typical shot. a) the beginning of the prebreakdown phase is from $t=0$ ns (closure of S_1 in Fig. 1) up to the moment the breakdown takes place at $t=330$ ns. The rise time (10% to 90%) of the voltage impulse is 235 ns, while the *displacement current* is negligible b) the total duration of the discharge is about 8 μs . The letters are corresponding to those in Fig. 12.

Fig. 9. Pressure pattern generated at 1.076 m distance by the HPU (in polar coordinates). The position of the electrodes is shown in the center, with 0 degrees corresponding to perpendicular to the electrode axis. The maximum corresponds to a pressure of 184 kPa.

Fig. 11. Time dependence of the Joule energy deposited in the load. The vertical dotted line represents the breakdown time i.e., the end of the pre-breakdown phase. The maximum energy reached is 7.4 J.

D. Efficiency of energy conversion

The acoustic energy carried at a time t by the pressure pulse generated by the HPU can be calculated based on the data of Fig. 9 and Fig. 14. Consider that the normalized pressure data P_k of Fig. 9 has been collected at N different angles θ_k , with $k=1, \dots, N$. In this case the acoustic energy W_a can be calculated as [16]:

$$W_a = \frac{1}{2} \rho v \int_0^t \left(\sum_{k=1}^N P_k^2 \right) dt \quad (5)$$

where $r=1.076$ m is the radius of the sphere on which the measurement is performed, $\rho=10^3$ Kg/m³ is the mass density of water, $v=1480$ m/s is the speed of sound in water; the area of a spherical segment A_k was calculated using spherical coordinates as:

$$A_k = 2\pi r^2 \sin\theta_k \quad (6)$$

and finally, the time integral is performed using the pressure pulse $p(t)$ of Fig. 14. The result of the calculations is presented in Fig. 16 and shows the maximum acoustic energy carried by the pressure pulse is $W_a^{max} = 62$ mJ. The energy efficiency is therefore $\eta = \frac{W_a^{max}}{W_e} \times 100 = 0.8\%$.

E. Operation of the HPU with freshwater

A few tentative shots were performed with the acrylic tube filled with freshwater having a conductivity $\sigma_{fw}=500$ μ S/cm, with $\sigma_0 / \sigma_{fw} = 14.2$ being *smaller* than the voltage impulse rise time of 225 ns. The freshwater experiments used a different pin electrode and support assembly (not shown), that does not leave any metal surface uncovered, apart from the tip of the pin and the small exposed area on dome. For these tests the TC4034 hydrophone was placed 1 m distance from source and at 0 degrees (see Fig. 9). The results are presented in Figs. 17 and 18 and show a lower peak voltage (80 kV) and a pressure of only 78 kPa, representing 89% of the value generated by the source at the same position when using deionized water. The lower efficiency is due to the *conduction* current reaching 280 A during the pre-breakdown phase, which corresponds to an amount of Joule energy being used less efficiently.

IV. CONCLUSIONS AND THE WAY AHEAD

A supersonic underwater HPU was demonstrated to generate a peak pressure of 184 kPa (225 dB re 1 μ Pa/V) at 1 m when operated in deionized water and 78 kPa in freshwater. The HPU is only using 7.4 J of electrical energy and therefore can be made very compact and at least in principle, by changing the HV charger, the closing switch and the electrodes, it can be operated at a very high PRF. The pressure profile of the source was found to display a resemblance to a far field dipole antenna radiation pattern. Using an ultrahigh speed camera, an optical study revealed highly complex inter-electrode plasma dynamics. When operated with deionized water, the efficiency

Fig. 12. Ultrahigh speed camera photos taken during 'identical' HPU shots with an exposure time of 3 ns. The time origin is from the beginning of the discharge i.e., the closure of S_f in Fig 1. The letters are corresponding to those in Fig. 10.

of energy conversion from electrical to acoustic was estimated to be 0.8%.

Plans for future include a detailed analysis of plasma streamers using the Schlieren technique and operation of the HPU source at a PRF of 1 kHz.

MS#

Fig. 13. Pressure signals generated by the two hydrophones, as recorded on oscilloscopes. Upper trace: the TC4034 hydrophone output is negative and without use of a preamplifier. Lower trace: the NH2000 hydrophone output is positive and uses a preamplifier. Note the early, large signal due to the electromagnetic interference at $t=0 \mu\text{s}$ when the spark-gap S_1 in Fig. 1 is closing. For a short time both hydrophones are upset. The main pressure pulse arrives at the hydrophones after $727 \mu\text{s}$, corresponding to a distance travelled by the sound of 1.076 m . The inserts present details of the pressure pulses recorded.

Fig. 14. Pressure pulse obtained from data presented in Fig. 13 using the analysis technique detailed in text. The pressure at the first peak is 184 kPa . The time origin corresponds to $715 \mu\text{s}$ from the closure of S_1 of Fig. 1.

Fig. 15. FFT of the pressure pulse presented in Fig. 14.

Fig. 16. Time dependence of acoustic energy carried by the pressure pulse of Fig. 14. The total acoustic energy is 62 mJ . The acoustic energy produced by pre-breakdown phenomena can clearly be identified as the small shoulder prior to the sharp rise corresponding to breakdown.

Fig. 17. Voltage and current signals during a typical shot with the HPU functioning with *freshwater*. During the pre-breakdown phase, the *conduction current* reaches 0.28 kA . Due to this large value, the voltage is only able to reach about 80 kV .

Fig. 18. Pressure pulse measured with the TC4034 hydrophone at 1 m from the HPU source functioning with *freshwater*. The peak pressure is 78 kPa .

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