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ELECTRO-OPTIC KERR EFFECT MEASUREMENTS OF INTENSE PULSED ELECTRIC FIELDS IN WATER

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Abstract

Loughborough University (UK) and the University of Pau (France) have begun a joint research activity into a novel and non-invasive pulsed electric field food processing technique. As part of this programme, the reliable measurement of the intense transient electric fields generated in the near field of an antenna immersed in water is essential.

Both research centres are currently developing fast electro-optic measurement systems based on the Kerr effect in water, as this approach offers considerable advantages over conventional D-dot sensors. A short list of these includes the important facts that an optical measurement is non-invasive, with only a laser beam traversing the water media, and has complete immunity to any perturbing electromagnetic influence from nearby powerful and usually very ‘noisy’ repetitive high-voltage generators.

The paper will present the main results obtained from the initial phase research effort into the accurate determination of the Kerr constant in water, for an electric field strength exceeding 300 kV/cm. This will be followed by details of the design of a Kerr sensor operating in the near field of an immersed high-voltage electrode.

The paper will conclude with a mention of the intended way forward.

I. INTRODUCTION

The use of pulsed electric fields (PEFs) is a mature technology used in the industrial processing of food, for example fruit juice. It is however restricted to liquid (‘pumpable’) food and involves metal electrodes in direct contact with the foodstuff – i.e. it is at present an inherently ‘invasive’ technology.

Loughborough and Pau Universities have begun a collaborative experimental programme aimed at demonstrating a new and ‘non-invasive’ approach (NI-

PEF) that will use water-immersed antenna, coupled to a repetitive fast high-voltage pulse generator to produce intense pulsed electric fields. The two centres have produced different designs for the driving pulsed power generator: one at Loughborough based on Tesla technology and the other one at Pau based on the Marx technique. A first machine that has been built and undergone preliminary testing uses a Tesla-transformer-based pulse forming line (PFL) generator assembled at Loughborough and coupled to a Valentine antenna designed at Pau to produce very intense electric fields in water (see Fig 1).

The measurement of the intense electric fields generated in water in the immediate vicinity of an antenna constitutes however a major challenge, as commercially available D-dot sensors are unsuitable for this task. A possible first and relatively simple way to measure such strong fields is to use a mm-size single-turn B-dot sensor (i.e., a dipole antenna) from which the electric field can be inferred. This technique has been investigated, but requires relatively complicated data analysis and is very sensitive to various electromagnetic perturbations from the nearby environment.

By far the best way to accurately and unequivocally measure PEFs, is to use electro-optic phenomena, such as the Pockels or the Kerr effects. As water is the medium in which the measurement takes place, it naturally follows that the Kerr effect in water is the simplest phenomena that can be exploited to perform the measurement. Unfortunately however, the value of the so-called Kerr constant for water (the Kerr ‘constant’ actually depends on water temperature and pressure, light frequency, electric field intensity, etc), is not accurately known, with numerous references providing *extremely contradictory data*. After an introduction of the Kerr effect, the present paper presents the results obtained from experimental efforts, both Loughborough and Pau Universities, to determine accurately the Kerr constant of water under experimental conditions similar to those to be used later in the first non-invasive PEF trials.

Finally, the paper presents the design of the Kerr electro-optic system intended for installation in water close to a high-voltage electrode. A mention of the way ahead concludes the paper.



Figure 1 NI-PEF system installed at Loughborough

II. THE KERR EFFECT

The Kerr electro-optic effect is produced by the interaction of an electric field with an isotropic substance, such as a liquid, inducing optical birefringence. The locally induced birefringence is a quadratic function of the electric field strength

$$n_{\uparrow\uparrow} - n_{\uparrow\rightarrow} = \lambda B E^2 \quad (1)$$

where $n_{\uparrow\uparrow}$ and $n_{\uparrow\rightarrow}$ are the refractive indices for the light with the electric vector respectively parallel and perpendicular to the applied polarizing external field E , λ is the light wavelength and B is the Kerr constant. The resulting retardation δ between the two electric field components of linearly polarized light launched along a direction perpendicular to an *homogeneous* external electric field is:

$$\frac{\delta}{2} = \frac{\pi l}{\lambda} (n_{\uparrow\uparrow} - n_{\uparrow\rightarrow}) = \pi l B E^2 \quad (2)$$

where l is the light path length under the influence of the external electric field. When the electric field is *non-homogeneous*, the retardation is expressed as:

$$\frac{\delta}{2} = \pi B \int_0^l E(x)^2 dx \quad (3)$$

When an external *time dependent* and *non-homogeneous* electric field is generated by an antenna, the retardation

can be determined at any time t by recording the time variation of the corresponding light intensity $I(t)$:

$$I(t) = I_{\max} \sin^2\left(\frac{\delta(t)}{2}\right) = I_{\max} \sin^2\left(\pi B \int_0^l E(x, t)^2 dx\right) \quad (4)$$

where I_{\max} is the maximum light intensity. In the case of a Kerr sensor, Equation (4) allows the time variation of the applied electric field to be obtained, but only if its spatial distribution inside the probe is calculated using commercially available software and the constant B is accurately known.

III. KERR WATER CELLS

As detailed above, one of the issues when measuring electric fields using the Kerr effect is the need for an accurate knowledge of the Kerr constant B over the broad range of parameters (electric field intensity, temperature and perhaps pressure) which will be encountered while performing NI-PEF processing. As the literature provides many contradictory results, an accurate determination of B is clearly required. To achieve this, the electric field integral in Equation (4) must be performed with great accuracy and therefore a simple electro-optic arrangement is useful. If the electric field is produced between a pair of flat electrodes immersed in water forming a so-called Kerr Water Cell (KWC), and a transient voltage $V(t)$ is applied from a high-voltage impulse generator, equation (4) can be simplified to:

$$I(t) = I_{\max} \sin^2\left(\frac{\pi B l' V^2(t)}{d^2}\right) \quad (5)$$

where d is the electrode separation and l' the *effective* path length, taking into account the effects of fringing fields at the plates edges. *An electrostatic solver must then be used to calculate the field integral in Equation (4) and thus determine l' .*

At both Loughborough and Pau, various KWCs have been designed, manufactured and used to determine the water Kerr constant B , and results from these studies are presented below.

All KWCs in these studies use basically the same electro-optic arrangement in which two immersed metallic electrodes are mounted inside the cell with their flat surfaces parallel to one to another at a distance d . The particular electrode geometry, together with various metallic and plastic materials used in the construction of the KWCs, all influence the *electric field distribution* along the laser beam which is taken account when the field integral is calculated.

The KWC electrodes (E) are connected to a pulsed power generator and the voltage impulses produced across them are accurately measured using a high-quality voltage sensor.

The optical system, shown in Figure 2, is similar for all the KWCs developed at both research centres.

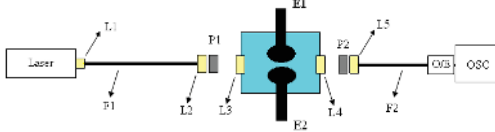


Figure 2 Water Kerr cell (schematic); for details, see text

A solid state 658 nm CW laser, mounted in a Faraday cage, launches light (using a lens $L1$) into a long optical fibre ($F1$), terminated by a collimator ($L2$) mounted close to a first polarizer ($P1$) that polarizes the light entering the KWC. $P1$ is not necessary if a polarisation maintaining fibre is used as $F1$. The light beam inside the cell is further compressed by a pair of convex lenses ($L3$ and $L4$) and, after emerging from the KWC, it is analyzed by a second polarizer ($P2$) before being collected by a second collimator ($L5$) and launched into another long optical fibre ($F2$) connected to a wideband opto-electronic (O/E) converter. This is attached to a digital oscilloscope (OSC) also placed in a Faraday cage, remote from the experiment and powered by a UPS, and used to record the time-dependent light variation $I(t)$.

IV ERRORS IN DETERMINING THE KERR CONSTANT USING A KWC

In what follows only experiments with a Kerr cell maintained at *constant temperature* and *atmospheric pressure* are considered. If a high-voltage impulse $V(t)$ is applied at the KWC electrodes, the Kerr constant is found from Equation (5) as:

$$B = \frac{\delta(t)d^2}{2\pi l'V(t)} \quad (6)$$

where the retardation $\delta(t)$ at any time t can be determined from the light intensity time variations $I(t)$ as presented below. By assuming small errors, the measurement is affected by the following uncertainties:

$$\frac{\Delta B}{B} = \pm \frac{\Delta \delta(t)}{\delta(t)} \pm 2 \frac{\Delta d}{d} \pm \frac{\Delta l'}{l'} \pm 2 \frac{\Delta V(t)}{V(t)} \quad (7)$$

detailed below.

i) **errors in determining the retardation** are calculated from the following equation

$$\frac{I(t)}{I_{\max}} = \sin^2\left(\frac{\delta(t)}{2}\right) \quad (8)$$

and after tedious calculation, the magnitude of the error is found as:

$$\frac{\Delta \delta(t)}{\delta(t)} = \left| \frac{\cos^{-1}\left\{(-1)^n \left[1 - 2 \left(\frac{I(t)}{I_{\max}} \pm \Delta \left(\frac{I(t)}{I_{\max}}\right)\right)\right]\right\} - \cos^{-1}\left[(-1)^n \left(1 - 2 \frac{I(t)}{I_{\max}}\right)\right]}{n\pi + \cos^{-1}\left[(-1)^n \left(1 - 2 \frac{I(t)}{I_{\max}}\right)\right]} \right| \quad (9)$$

where n is an integer defined by $\frac{\delta(t)}{\pi} = n + k$ and k can take values between 0 and 1. The error can be calculated from the phase shift $\frac{I(t)}{I_{\max}} + n$, directly obtainable from

the $I(t)$ oscillogram. Because water has a small value of B , the phase shift in the experiments is rather low. The experimental recording contains, apart from the inherent noise of both the oscilloscope and the opto-electronic sensor, a supplementary optical noise due to various reflections in the optical system. The time for making the best measurement is when the light intensity $I(t)$ reaches a zero. If we consider that the phase can be read with a precision of say ± 0.1 degrees then from (9) the best estimate of the corresponding error in obtaining the retardation angle is then about $\pm 2\%$.

ii) **errors in determining the distance between Kerr cell electrodes** are related to the actual practical arrangement. Without taking exceptional measures this distance, say 3 mm, can only be measured with a precision of about $\pm 50\mu\text{m}$, resulting a total error of about $\pm 3\%$.

iii) **errors in determining the effective path length** are difficult to be estimated, but using state-of-the-art 2D or 3D electrostatic solvers, the effective path length for an infinitely thin light beam, perfectly aligned between and parallel to the electrodes surface (whatever their geometry), can be calculated with practically no measurable error.

iv) **errors in the measurement of the high-voltage impulse across the Kerr cell** are related to two, very different aspects.

The error introduced by the voltage sensor itself is, in the best case, somewhere between $\pm 2\%$ and $\pm 3\%$, with the corresponding error in the Kerr constant being between $\pm 4\%$ and $\pm 6\%$. There is however another, more subtle, source of error. When a voltage sensor is connected in parallel with the Kerr cell electrodes, the impulse voltage measured by the oscilloscope is given by:

$$V_{\text{oscilloscope}} = V_{\text{capacitive}} + V_{\text{resistive}} + V_{\text{inductive}} \quad (10)$$

The effect of the inductive term in Equation (10) on the accuracy of voltage measurement is never mentioned in the literature on Kerr data although, judging from the available description of the arrangements, the self-inductance of the electrical connections is probably large. If a *very low-frequency* voltage impulse is applied, or the measurement is made during the plateau of a multi-microsecond rectangular voltage pulse, as is the norm in most published works, the inductive voltage term may not be important. However, all data in the present programme has been corrected using a numerical technique which will be presented elsewhere.

As a *conclusion on the errors in determining the Kerr constant for water using a KWC*, it is obvious that without exceptional measures, the total systematic error could be well in excess of $\pm 10\%$. This provides a convenient explanation for many of the differences existing in the related literature and also sets a limit to the precision expected from the use of a Kerr water sensor.

V. DETERMINATION OF WATER KERR CONSTANT

A. Results obtained at Loughborough

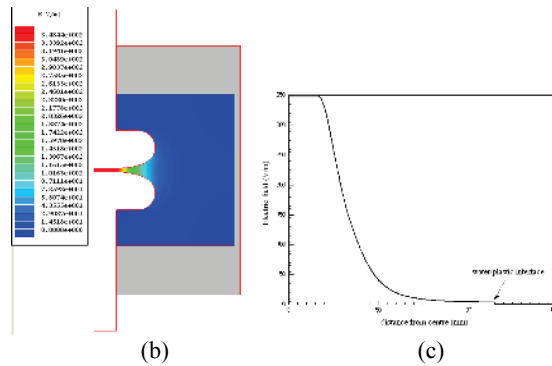
Two different KWCs have been designed, constructed and tested at Loughborough.

KWC-L1 (Figure 3(a)) uses a pair of near Bruce profile stainless-steel electrodes separated by a distance $d = 2.87 \pm 0.05$ mm and for which the electric field distribution has been determined (Figure 3(b) and (c)) using 2-D Maxwell SV software. Calculation of the integral in Equation (4), using the same software, resulted in an effective length $l' = 5.30$ mm. Voltage impulses up to 100 kV can be generated by a trigger generator (TG-70) and, as the KWC-1 impedance is much larger than the characteristic impedance of the output coaxial cable from the TG-70, a number of reflections are produced and conveniently used as a train of high intensity electric field impulses in the electro-optic experiments. The results presented in Figure 4 are representative and show both the time dependence of the central homogeneous electric field calculated as $E(t) = V(t)/d$ with $V(t)$ obtained experimentally (upper part of Figure 4) and the corresponding experimentally recorded time dependence of the light intensity (lower part of Figure 4(b)). The same median B value of $2.45 \cdot 10^{-14}$ m/V² was obtained in all experiments for electric fields up to about 300 kV/cm. The light intensity obtained experimentally can then be compared with the light intensity calculated from Equation (5) using the voltage data $V(t)$ and the median value for B (lower part of Figure 4).

KWC-L2 uses a pair of 400 mm long parallel-plate stainless-steel electrodes, placed a distance $d = 5.00 \pm 0.05$ mm apart, with the aid of polyethylene supports (Figure 5(a)). An electric pump, coupled to the cell through plastic tubes, allows removal of any impurities produced during discharges and is essential for future temperature-controlled experiments. The electric field distribution and the corresponding electro-optic effective length will be evaluated using 3-D Maxwell software. Typical results obtained with KWC-L2, powered by the same TG-70 generator, are presented in Figure 6. Because its corresponding values for retardation for the same applied voltage are much larger than those produced by KWC-L1, KWC-L2 allows a more accurate determination of the Kerr constant. A polarimetric arrangement is being implemented to increase even more the precision of the optical measurements.



(a)



(b)

(c)

Figure 3 KWC-L1

(a) ready for mounting on the optical bench (b) electric field strength mapping for 1 V applied; note that all metallic and plastic components are taken into account (c) the corresponding electric field distribution along the laser light path. Because of the symmetry in both (b) and (c), only the right-hand half of the arrangement is shown.

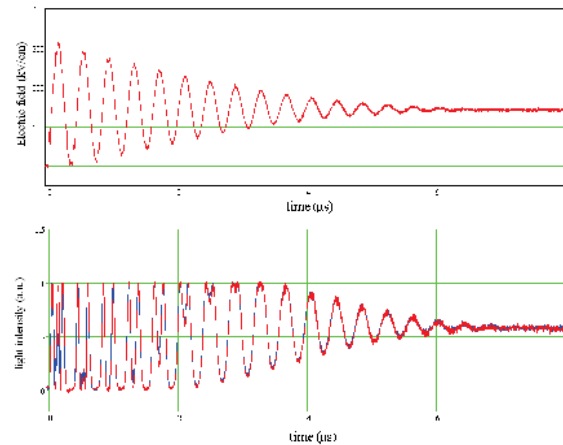


Figure 4 Typical results from KWC-L1 experiments Time variation of the central electric field (upper trace) and corresponding modulation of light intensity obtained experimentally (lower red trace) and theoretically (lower blue trace). For details see text.

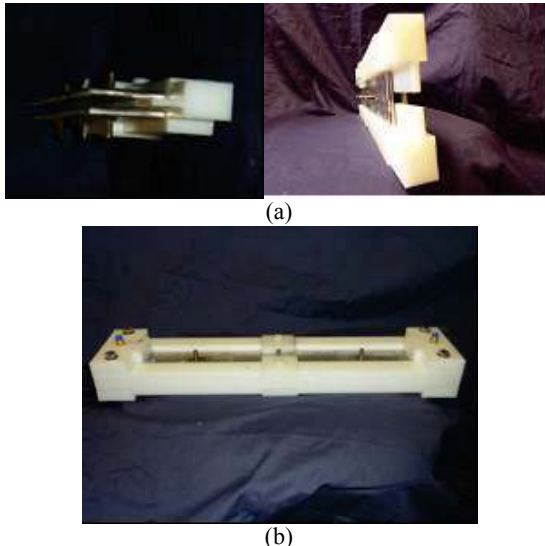


Figure 5 KWC-L2

(a) electrode details (b) ready for mounting on the optical bench

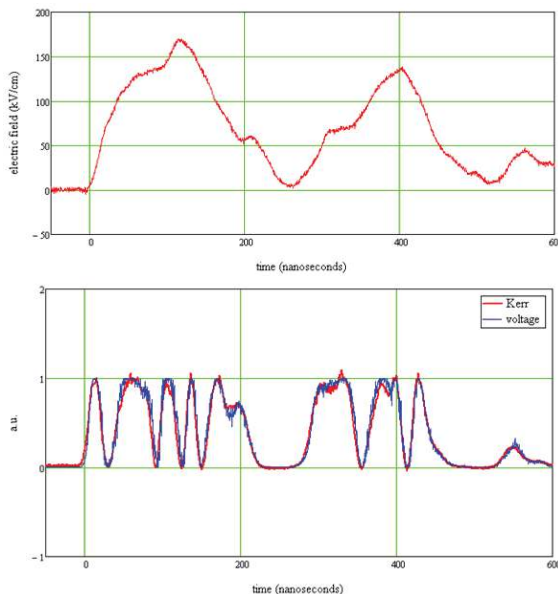


Figure 6 Typical results from KWC-L2 experiments Time variation of the central electric field (upper trace) and the corresponding modulation of light intensity obtained experimentally (lower red trace) and theoretically (lower blue trace). For details see text.

B. Results obtained at Pau

An original KWC has been designed, constructed and tested at Pau. The KWC-P (Figure 7(a)) uses a pair of near Rogowsky profile stainless-steel electrodes placed in water at a distance d adjustable between 2 mm and 3 mm with a precision of ± 0.05 mm and has a calculated effective light path length $l' = 31$ mm. The complete map of the electric field strength inside the KWC-P shown in Figure 7(b) was obtained using a specialised electrostatic

solver (Quickfield). All the experimental results were obtained using an inter electrode distance $d = 2.4$ mm, and water at a temperature of 22°C . Due to the optical signal noise, generated by reflections inside the optical system, the bandwidth of the corresponding oscilloscope was limited to 250 MHz and the same bandwidth was used in the oscilloscope used to measure the voltage impulses applied across the KWC-P electrodes. These are generated by a Marx generator having an output capacitance of 1.7 nF [1], with the generator pressurised with nitrogen at different values between 4 bars and 8 bars, when operated at peak output voltage levels between 59 kV and 90 kV. The results shown in Figure 8 are representative for the type of voltage waveforms generated by the Marx generator pressurised at 5.5, 6 and 7 bars and their corresponding Kerr signals. The figure shows both the time dependence of the central homogeneous electric fields, calculated as $E(t) = V(t)/d$ (with $V(t)$ obtained experimentally) and the corresponding experimentally recorded time dependent light intensities. The number of oscillations in the light intensity is related to the ratio of the applied voltage amplitude on the cell constant: a parameter which at constant temperature is fixed by the cell geometry and the Kerr electro-optic coefficient of the liquid. As observed, the central oscillation of the Kerr optical signal increases with the electric field level in agreement with theoretical prediction. The same *median* B value as obtained at Loughborough i.e., $2.45 \cdot 10^{-14} \text{ m/V}^2$, was determined in all experiments for electric fields in excess of 370 kV/cm. The time variation of the light intensity obtained experimentally can then be compared with theoretical predictions using Equation (5) and the voltage data $V(t)$, together with the median value for B (Figure 8, part (b)).

V. CONCLUSIONS

Results have been presented from a joint Loughborough-Pau research programme aimed at demonstrating a novel non-invasive PEF technology.

The Kerr constant for water at 658 nm, 22°C and for transient electric field intensities in excess of 370 kV/cm with durations from a few tens of nanoseconds to a few microseconds was determined as $2.45 \cdot 10^{-14} \text{ m/V}^2 \pm 10\%$. Experiments to determine the variation of the water Kerr constant with temperature are planned for the near future. This will allow the calibration of the electro-optic Kerr sensors to be used in the measurement of the intense transient electric fields to be generated during future proof-of-principle experiments to demonstrate the novel non-invasive food processing technique.

VI. REFERENCES

- [1] B. Cadilhon, L. Pecastaing, T. Reess, A. Gibert, Low stray inductance structure to improve the rise-time of a Marx generator, *IET Electric Power Applications*, Vol 2 Issue 4, pp. 248-255, 2008

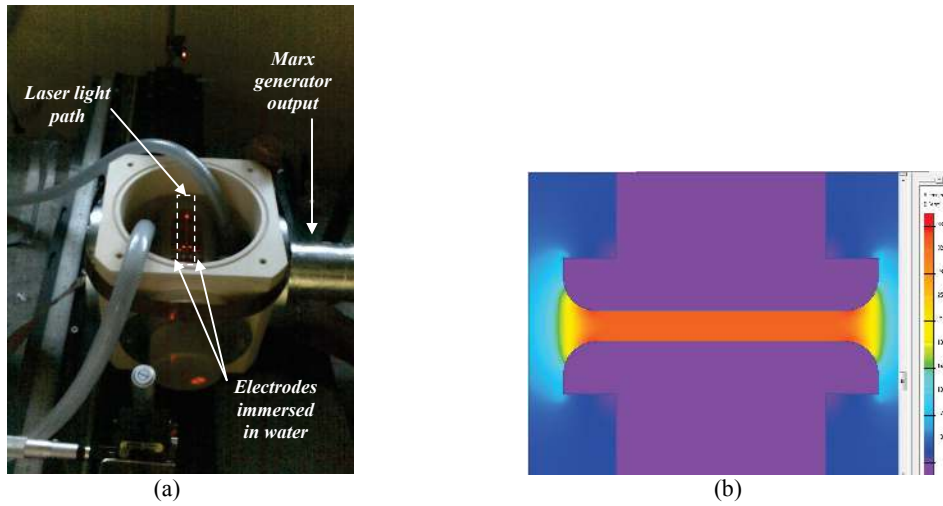


Figure 7 KWC-P

(a) electro-optic arrangement showing the laser light path
 (b) simulated electric field distribution inside the cell, corresponding to the light path

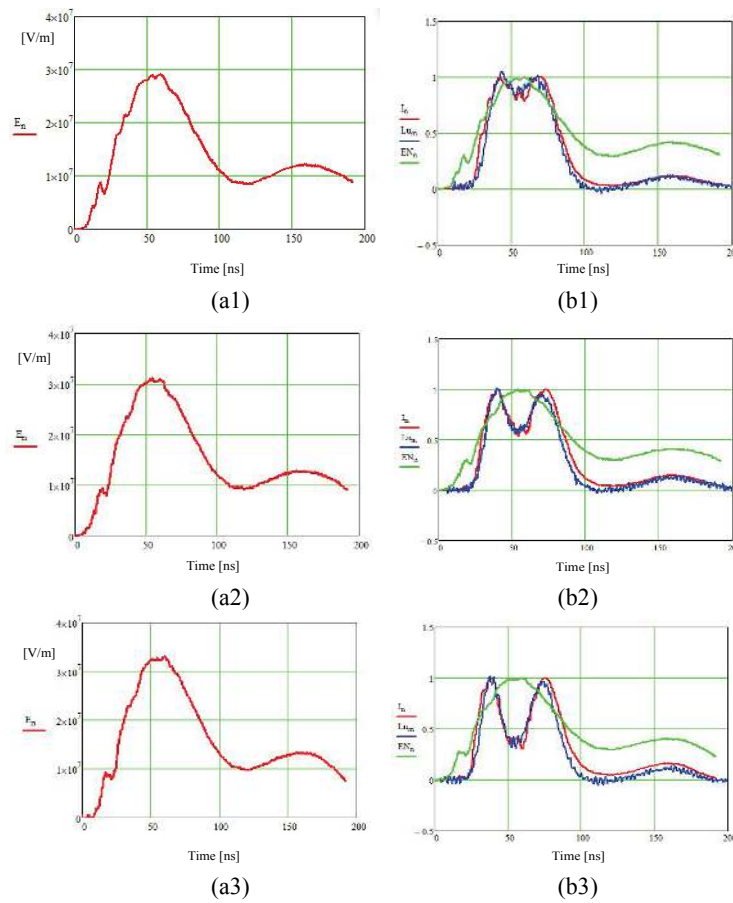


Figure 8 Typical results from *three* typical KWC-P experiments

Marx generator pressurised at 5.5, 6 and 7 bars to produce a peak output voltages of 70, 74.8 and 79.2 kV.

(a) time variation of the central electric field; (b) corresponding modulation in the light intensity obtained experimentally (blue trace) and predicted theoretically (red trace) using the normalised electric field (green trace)