HIGH-VOLTAGE AND HIGH-POWER MULTI-PULSE POWER SOURCE

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Final Report. October 2001

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BACKGROUND

This one-year agreement relates to a method of generating multiple high-voltage pulses from the single discharge of a capacitor source, with the pulses produced by a special-purpose array of exploding wires. It is concerned with both the development of a computer model based on equations of state that describe the magneto-hydrodynamic processes inside the wire and the experimental verification of the model. The system is able to produce a series of up to three high-voltage pulses that can be used to drive radiation generators based on X-ray or microwave sources.

INTRODUCTION

This report is divided into two parts. The first of these is devoted to a theoretical study of exploding wires, together with results of experiment undertaken to benchmark the code. The second describes the practical work undertaken in the development of a high-power high-voltage twin-output driver for use with radiation generators.

THEORETICAL WORK

A magnetohydrodynamic code for exploding cylindrical wires has been implemented based on the Loughborough filamentary approach. The basic laws of physics together with the equations of state and electrical conductivity data are used to analyse the complex conditions that exist during the different phases (solid, liquid, vapour) that are attained by the wire as it explodes.

The **kinetic energy** is calculated using a homogeneous distribution of velocities within the wire, in a manner similar to that used in the well-known Gurney model used in high explosive work [1]. The **magnetic energy,** both inside and outside the wire is obtained using conventional electromagnetic techniques [2], and the **inductance** and **resistance** are determined taking into account non-linear diffusion [2]. Any **radial expansion** of the fuse is regarded as arising from the competing effects of internal kinetic pressure and external magnetic field pressure. The different phases are treated

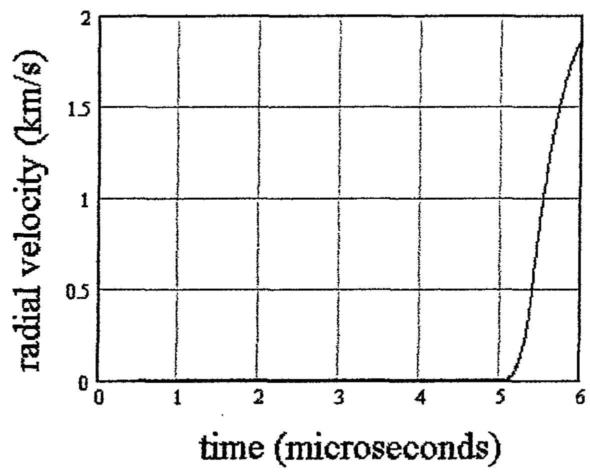

Figure 1 Outer surface radial velocity

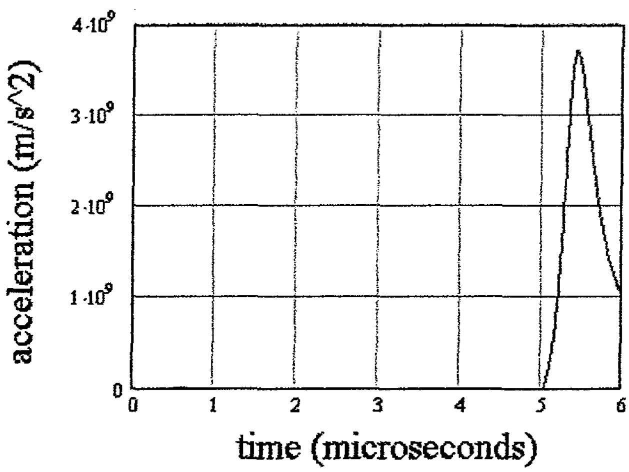

Figure 2. Outer surface acceleration

separately when any **phase transition** (melting or vaporisation) occurs within the conductor, with the interface conditions obtained as in [3] and [4].

During the development of the code, it was established that neither the electrical conductivity data available from the SESAME Library (LANL) nor the simple Burgess model of the Sandia National Laboratories accurately describe the ongoing phenomena. It was also found that this had been noted elsewhere [4,5]. The fact that the electrical conductivity does not follow the handbook variation with temperature while the wire is exploding in the liquid phase may be due to a radically different behaviour pattern during the very fast transition. Other research groups are known to have encountered the same difficulty. It was decided therefore to develop a model based on the Lee-More theory of electrical conductivity [6,7], as adopted previously by the Lindemuth group at LANL [4] for dealing with exploding foils.

Although no satisfactory models appear to exist for exploding wires used in high-energy implosions that start from cold conditions, new conductivity data has recently been received from Sandia National Laboratories for both aluminium and copper [8]. This has been obtained from a long and costly research activity and probably represents a significant breakthrough. However, due to the novel form in which the data is presented insufficient time was available to introduce it into the existing code.

As a final step in the code, the law of **energy conservation** provides a further equation that was used to check the accuracy of the results. By changing either the time step during the calculation or the integration method, the energy conservation law was maintained to within to 0.1%.

A full-scale exploding wire facility was designed and successfully tested at Loughborough. It was demonstrated that the current pulse is substantially affected by the surrounding medium and that the best pulse waveform is obtained when the surrounding medium is simply dry air. Results from an experiment done in order to benchmark the code (single copper wire, 125μm diameter, 170mm length, 25kV, 0.2kJ) are compared in Figs 1-5 with results predicted by the numerical code. More details related to the design of the exploding wire arrays used in the system are given in Section 1.2.

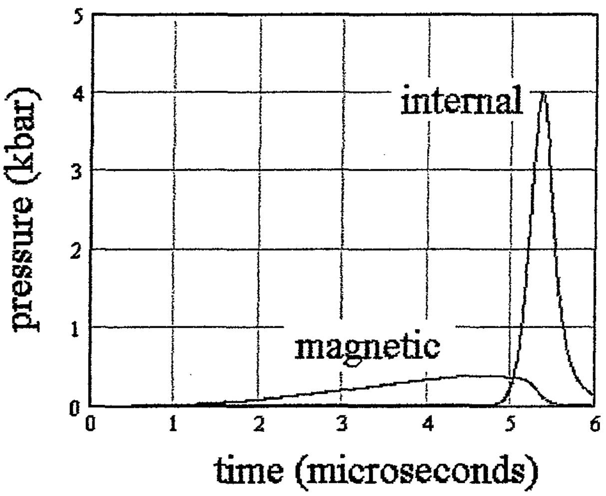

Figure 3 Magnetic and internal pressures

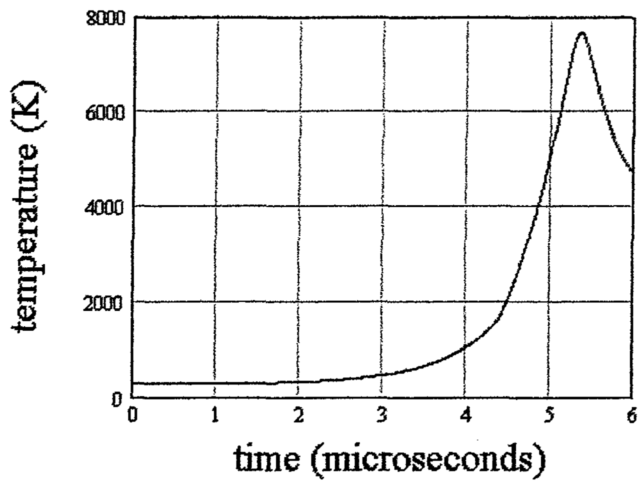

Figure 4 Inner core temperature

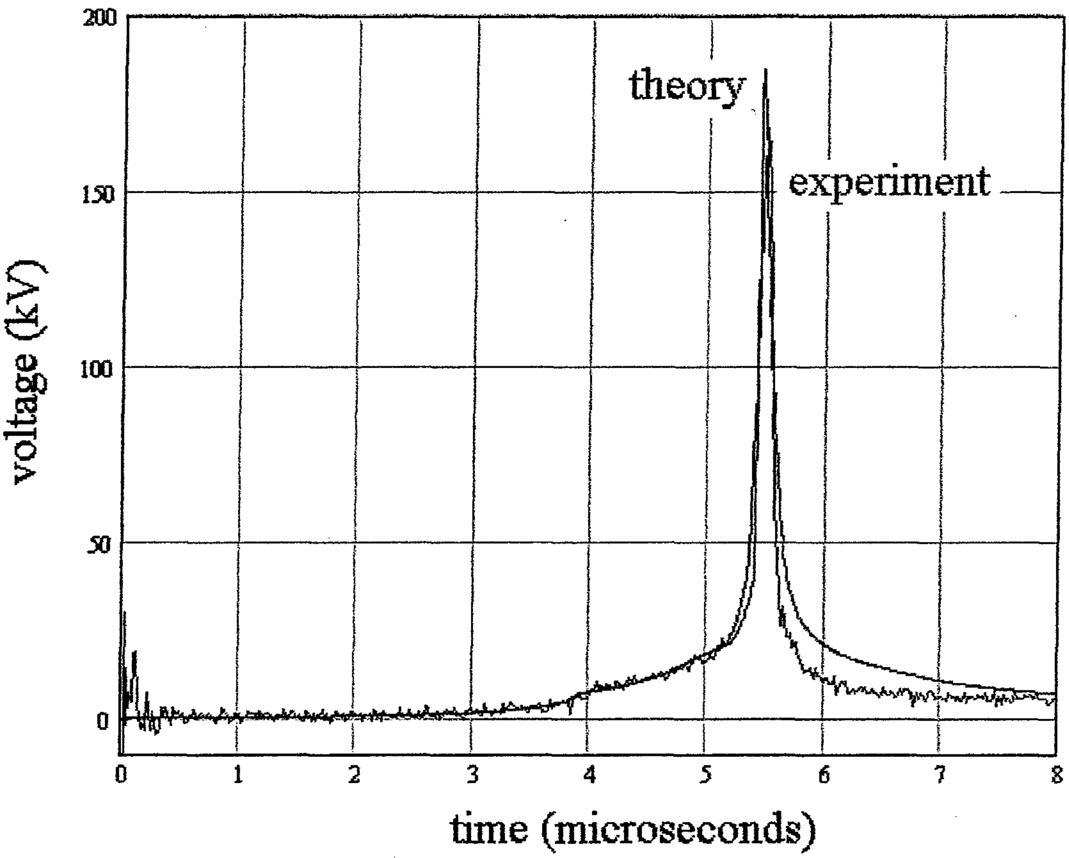

Figure 5 Voltage generated by exploding wire action (theory vs experiment)

Further theoretical considerations relating to the modelling of the complete multi-pulse power source are presented in Section 3.

EXPERIMENTAL WORK

1. Generator components and development

The equivalent electrical circuit for the generator is given in Fig 9. The different elements of the circuit are described below, together with the most important issues that arose during their development.

1.1 Energy source

The energy source for the generator was a 56.6 μF capacitor bank (C), charged to 25 kV (V_0) and connected to the transformers (T) through a parallel-plate transmission line and a simple pin-type closing switch (CS). The equivalent resistance and inductance of the capacitor bank circuit were 7 mΩ (R_{cb}) and 20 nH (L_{cb}).

1.2 Exploding wire arrays (EWA) as opening switch elements

Opening switches are necessary to produce the large and rapid negative excursions of current (dI/dt) that are needed in the primary circuit of the transformers to provide the required high-voltage pulses to the output loads. Exploding wires were used for the switches, as these are known to be more efficient than the foils used in an earlier low-energy system [9]. A large number of experiments were performed to establish the optimum tamping element for the wires. Air, water, sand (glass beads between 10 μm and 100 μm in diameter), epoxy and various gels (sealant) were all investigated, together with exploding wire arrays of copper wire with diameters between 50 μm and 250 μm. The well-known fact that thinner wires produce higher voltages when they explode was indeed confirmed, although the difference between the extremes of wire size used here was only about 10%. Because a large number of parallel wires were required if the thinnest (and most fragile) wires were used in the exploding wire arrays (EWAs), it was decided to adopt the more robust 250 μm diameter wire.

It was somewhat unexpectedly found that air was the best medium in which to operate the arrays, although the normal assumption is that higher voltages are generated when the medium is water. This is probably attributable to the fact that only very thin wires (well below 50 μm diameter) respond better in water and to the relatively short rise time of the current in the present system, which are not the conditions that applied when most of the data reported in the literature was obtained.

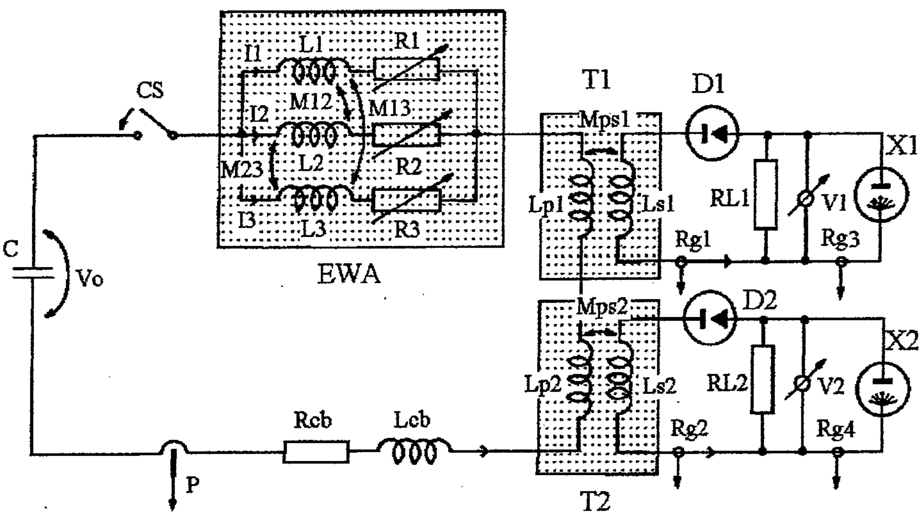

Fig.6 Electrical equivalent scheme for the high-energy system

A further important finding was that two parallel-connected EWAs can generate a much higher voltage than a single EWA, which could bring about *major improvements* in conditioning techniques using opening switches.

No measures were taken to alleviate any effects of the powerful shockwaves resulting from firing the EWAs in open air, but in future systems the EWAs could be mounted in closed and pressurised vessels. Fig 7 shows a 200 kV voltage pulse generated across a cylindrical EWA, representing an eightfold increase in the initial charging voltage. This result compares favourably with the best previous results using similar EWAs obtained at both the Naval Research Laboratory (USA) [10] and Texas Tech University [11], but in pressurised containers and fine quartz sand respectively. The parameters of all the EWAs used in the high-energy system are given in Table I.

Table 1 EWA main parameters

No of train pulses	EWA 1				EWA 2				EWA 3			
	L_1	N_1	w_1	G_1	L_2	N_2	w_2	G_2	L_3	N_3	w_3	G_3
1	50	13	300	C	-	-	-	-	-	-	-	-
2	220	7	180	R	500	9	390	R	-	-	-	-
3	100	10	110	C	250	9	200	R	520	10	160	R

L, N and w are inductance (nH), number of parallel wires and wire length (mm)

EWA geometry (G) is either cylindrical (C) or rectangular (R)

1.3 High-voltage air-cored transformers

Although for the low-energy system a very compact oil filled transformer was developed and successfully operated at up to 300kV [9], it was decided nevertheless to use a simpler but extremely robust air-cored transformer in the present system. A high dielectric-strength Melinex film bonded with a polyethylene layer and having a thickness of 250 μm is commercially available, and by thermally bonding adjacent polyethylene layers with an intervening 0.1 mm thick 0.5 m wide copper foil a flat long (15 m) sandwich-like structure is produced. Additional inter-winding layers can readily be added, to accommodate an increased electric stress. Both the single turn primary and the 15-turn secondary windings were produced in this way. The main parameters of the 300 kV design transformer are: primary/secondary/mutual inductance 115 nH / 22 μH / 1.5 μH, with a resulting very high coupling factor of 0.94. Increasing the insulation thickness would enable the same basic design to be used up to 500 kV. Surface breakdown provided the main difficulty encountered during the development of the transformer. Standard single-pulse textbook formulae proved invalid for the present multi-pulse system. It was found that a surface length of about 60 cm was required to prevent surface breakdown when two 250 kV pulses were generated, but this length had to be almost doubled to withstand a sequence of three 200 kV pulses.

1.4 Resistive load and diagnostics

The high-voltage high-power resistive load (RL) developed at Loughborough is a water resistor doped with copper sulphate to give a resistance of several tens of ohms. The dimensions of the voltage insulators necessary to avoid surface breakdown were obtained experimentally. In situ current and voltage measurements were made for each experiment using respectively Rogowski coils (Rg) and high-voltage probes (V). Accurate calibration was thus made possible, as this type of resistor is sensitive to both temperature and ageing. The two voltage sensors were 500 kV fast capacitor dividers mounted in oil barrels. When X-ray sources (X) were coupled to the transformer outputs, up to four fast Rogowski coils were used to monitor the different currents. A calibrated pick-up probe (P) positioned in a tunnel in the flat transmission line measured the main circuit current and its corresponding time rate of change.

1.5 Polarity dependent spark gap (diode), pre-pulse suppression and output pulse conditioning

As mentioned above, each voltage pulse on the load follows approximately the corresponding dI/dt in the main circuit. When multiple pulses are produced, the magnitudes of the negative pre-pulse and the positive pulses are close, meaning that a conventional spark gap cannot be used to remove the negative pre-pulse and to sharpen (condition) the positive pulses. It was therefore necessary to develop a polarity-sensitive spark gap (a diode D) for this purpose. This was based on the point/plane configuration described previously [9], in which the pronounced polarity effect results in a positive/negative voltage breakdown ratio of almost two. Fig. 8 shows the diode action resulting in both suppression and sharpening.

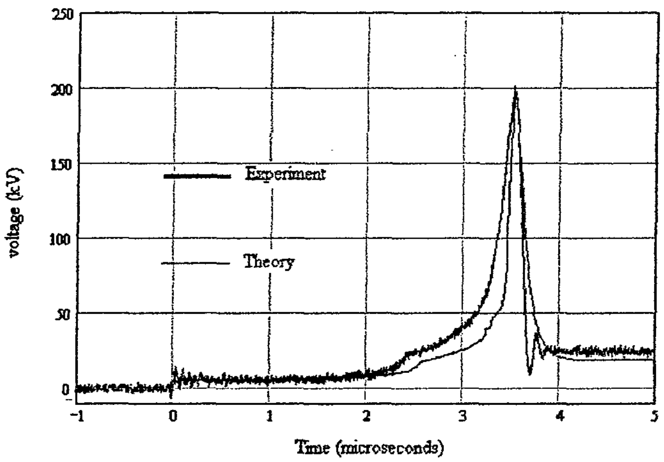

Fig.7 Voltage generated by EWA1 (one pulse, Table 1)

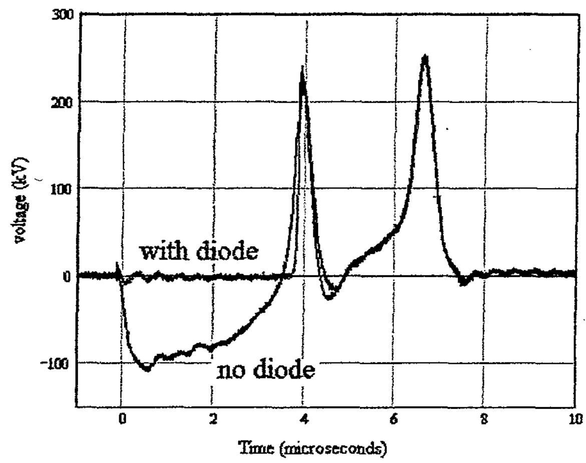

Fig.8 Diode action on a double-pulse output

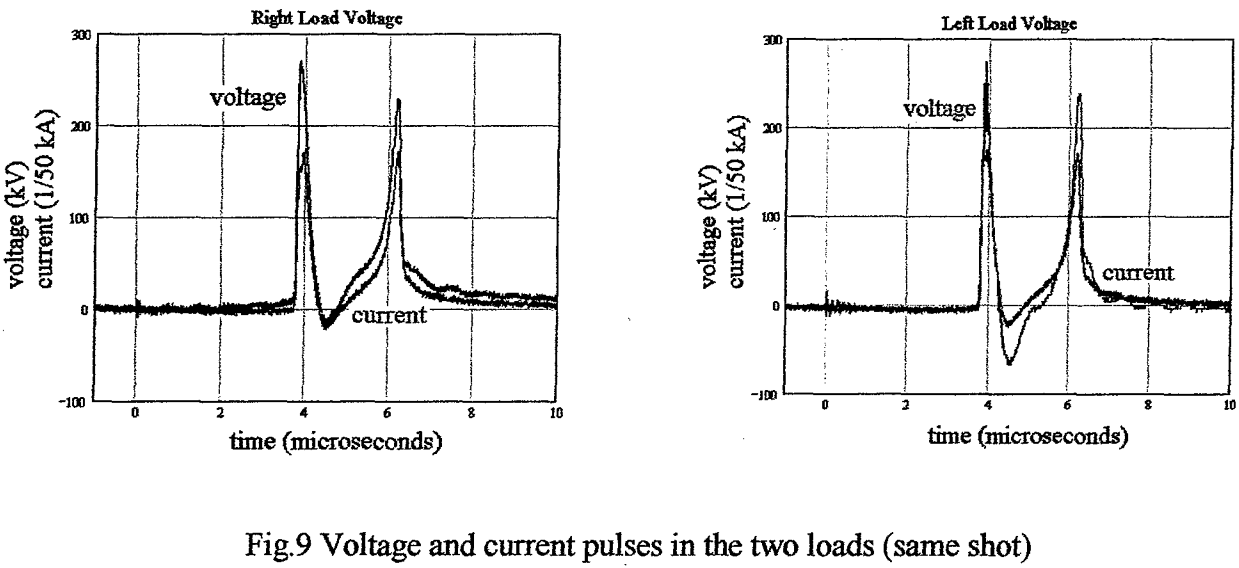

Fig.9 Voltage and current pulses in the two loads (same shot)

2 High-energy multi-pulse system

Although a detailed investigation of the single-pulse performance of the system was outside the main aims of the present research, all the indications, provided by testing of the appropriate cylindrical 200 kV EWA (Fig. 2) and from the benchmarked code, are that a pulse of about 500 kV can be produced at each output with increased insulation. In the double-pulse configuration, the system generated equal 250 kV (±15%) pulses at the two outputs (Fig 9). The rise time of the first pulse is 30 ns and with 75Ω loads the power in each pulse is almost 1 GW (Fig.10). It should be noted that, as a consequence of inductive effects, unequal voltage pulses drive equal current peaks through the loads (Fig.9).

The triple pulse configuration (see Table I for details of the corresponding EWAs) produced voltages up to 200 kV at each output (Fig 11). Although the time-delay between pulses can be varied, the total of all the pulse delays cannot exceed about 3.5 μs with the present equipment

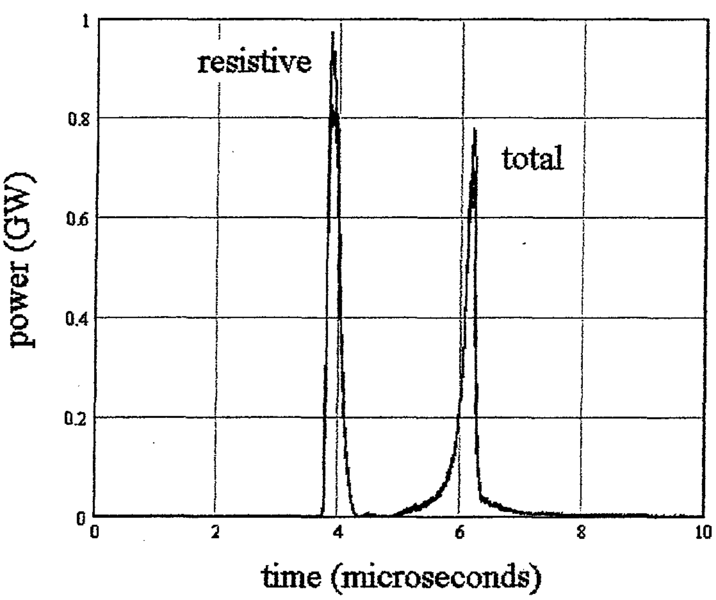

Fig.10 Load power

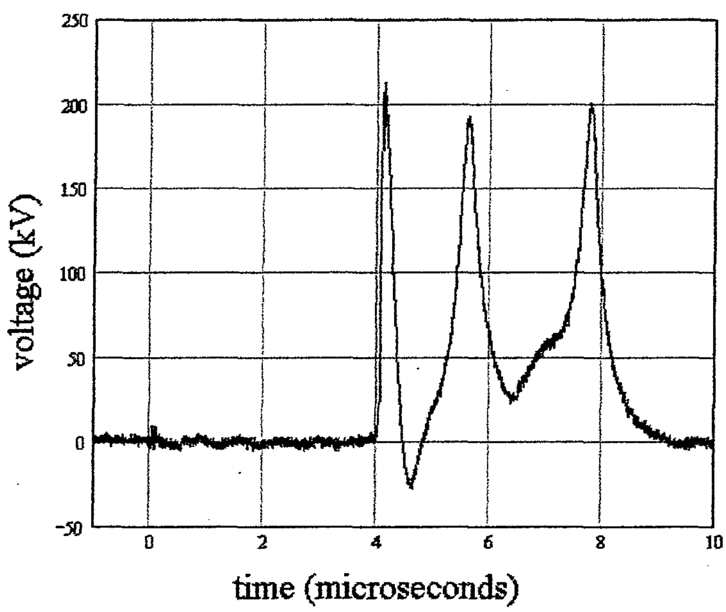

Fig.11 Three high voltage pulses

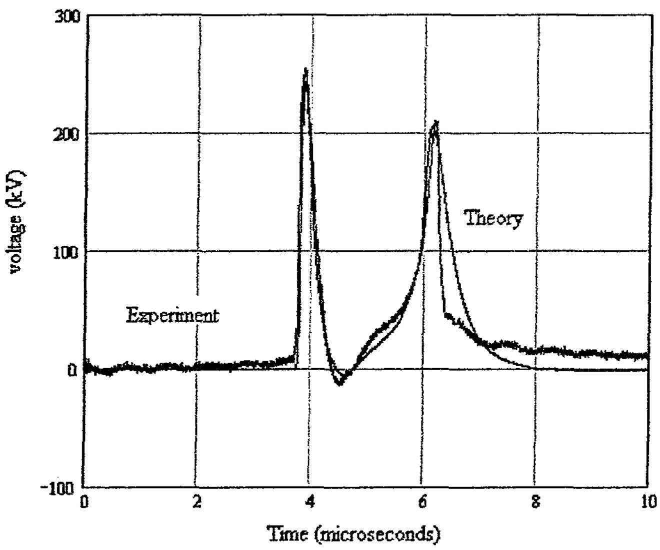

Fig. 12. Theoretical predictions versus experimental data

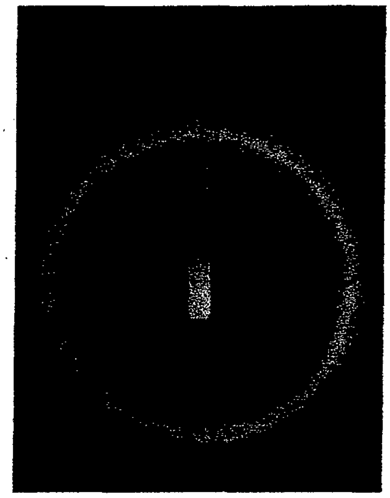

Fig. 13 X-ray picture

3. Complete system numerical modelling

Extensive numerical modelling was necessary during the development of the high-energy system with a detailed numerical code being developed for predicting the characteristics of the EWAs. The accuracy that was achieved is evident in Fig 7.Numerical modelling of the complete system employed the filamentary technique developed at Loughborough [9]. The predicted results were again extremely accurate, as is clear from Fig.12. About 100 runs of the code were normally required to investigate the multi- dimensional parameter space of each different design and to optimise the overall behaviour.

It was established that the EWA inductance primarily controls the time delay although the number of wires in parallel is also important. For a low inductance EWA a cylindrical geometry (C) was adopted, with an inner return cylindrical conductor, while for a high inductance EWA a rectangular cross section inductor (R) was constructed from a thin copper sheet with the exploding wires mounted on one of the faces (see Table I).

The pulse amplitudes were found to be controlled by the wire length.

4 X-ray generation and monitoring

X-ray heads were attached to the transformer outputs in parallel with resistive loads, to provide protection during the first moments of conduction when the tube impedance is very high. It was established experimentally that the optimum value for these resistors is 10 Ω, which in addition to protecting the transformer also limits the tube current to a safe level (some kA) during the second

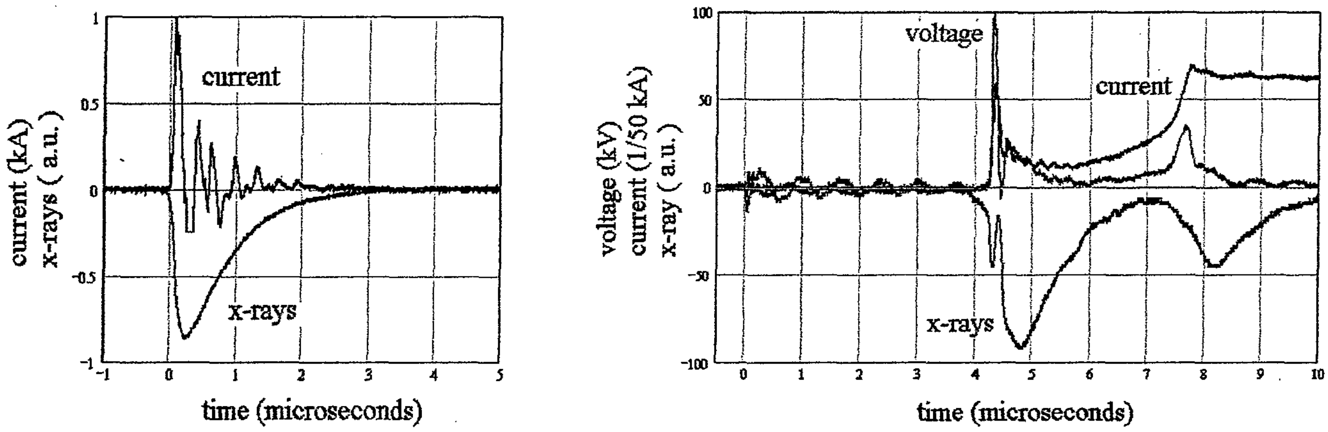

Fig. 14 X-ray monitoring (a.u. arbitrary units): current and radiation from a HP single-pulse flash X-ray system (left); voltage, current and radiation characteristics for an X-ray source driven by the Loughborough system (right)

pulse, when it is much higher than that during the first pulse. Since the time between pulses (about 3 μs) is not sufficient for the tube fully to recover its variable impedance stays low at around 25 Ω, much below the normal 75 Ω during the first voltage pulse . Fig 13 is an X-ray picture of a detonator obtained using the system. The time-dependent radiation from the tube was monitored using a special-purpose fast diode feeding an oscilloscope through a limited bandwidth amplifier. Fig 14 shows the results obtained from one of the X-ray sources during two-pulse operation, compared with corresponding results from a Hewlett-Packard single-pulse flash X-ray system.

CONCLUSIONS

A detailed numerical code to predict the behaviour of wires exploding under fast pulse conditions has been developed and benchmarked against reliable experimental data. The code has then been successfully in predicting the performance of a high-power source (Fig. 15) that produces either one pulse of about 500 kV, two 250 kV pulses or three 200 kV pulses at each of the two independent outputs. A power exceeding 3 GW can be generated in a single pulse. X-ray heads attached to the system successfully produced multiple pulses of radiation.

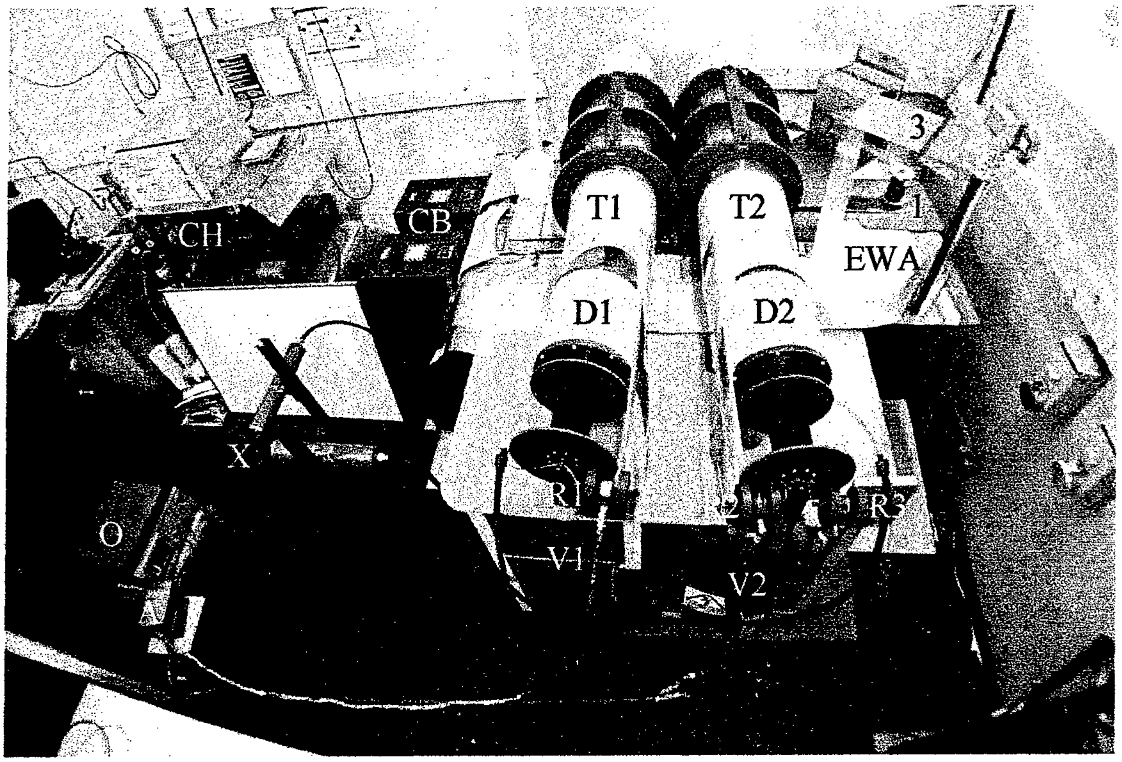

Fig. 15 Complete system (CH-HV charger, CB-capacitor bank, T-transformers, D-diodes, R-Rogowsky coils, V-voltage sensors, A-attenuators, O-oscilloscope, X-X-ray sources)

The generator can be extremely useful not only for X-ray cineradiography, but also as a high-power microwave driver. For this it will be necessary to merge the three pulses to obtain a single high-voltage step for almost 1 μs with a 30 ns rise time, ideal parameters for driving a vircator or a similar microwave emitter. Although designs for similar generators are now under development elsewhere the system described above appears to offer a technically superior solution.

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14. ABSTRACT

This report results from a contract tasking University of Loughborough as follows: The contractor will develop a method of generating multiple high-power and high-voltage pulses, from the single discharge of a capacitor source, with the pulses produced by an array of specially designed exploding wires. It will mainly be concerned with the development of a detailed computer model based on equations of state that describe fully the magnetohydrodynamic processes inside the wire, but will also involve verification of the model using an existing experimental facility.

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