Experimental and Theoretical Studies of a Flyer Plate Electromagnetic Accelerator

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ABSTRACT

A common initiative for the research into the physics and technology of a flyer plate electromagnetic accelerator has been started at AWE, Aldermaston and Loughborough University. Two electromagnetic accelerators have been constructed and tested: AMPERE, a 120 kJ / 40 kV capacitor bank system at AWE and QUATTRO a 100 kJ/30 kV capacitor bank system at Loughborough Pulsed Power Laboratory. Two numerical models for simulating the foil-flyer accelerator have been developed: a 0-D anda 2-D. The 0-D model is providing a useful tool for designing and for parametric studies and the 2-D model for accurately calculating all the details of the accelerator such as: the velocity, acceleration and temperature of the flyer the current distribution and the overall distribution of the magnetic and electric fields generated during a shot. The paper will present the most relevant experimental data obtained during the first phase of the joint programme and compare it with theoretical predictions.

Index Terms — **Electromagnetic accelerator, electromagnetic accelerators, pulsed power, filamentary modeling, electromagnetism**

1 INTRODUCTION

This paper presents the main results obtained during the first year of a joint AWE, Aldermaston, UK and Loughborough University (LU), UK research programme, involving the study and practical performance of a flyer plate electromagnetic accelerator. The final aim is to simulate the mechanical impulse generated on a plastic target by cold x-rays. When an accelerator is used, the impulse is produced from a thin layer of the target material being shocked outwards and at the same time, because of impedance mismatch an inwardly directed shockwave is produced to conserve momentum. This travels to the back surface of the target and cause mechanical damage such as spalling or delamination. In order to have a reliable and accurate effect in a planar target, it is necessary to create a planar shockwave which can then travel through the material.

2 ELECTROMAGNETIC ACCELERATORS

Two similar electromagnetic accelerator systems have been developed at the two research centers, both based on capacitor banks (Fig. 1) which have implemented a variable damping resistor in the form of a thin metallic foil or fuse. An experiment is performed by charging the capacitor, with the circuit open, followed by discharging it using a triggerable closing switch.

The AMPERE system (Fig. 2) uses a 120 kJ / 40 kV capacitor bank and an exploding aluminium foil as damping element, while the Loughborough system, termed QUATTRO (Fig. 3), uses a 100 kJ/30 kV capacitor bank and a non-exploding stainless steel foil wth the currents produced by the two systems presented in Fig. 4.

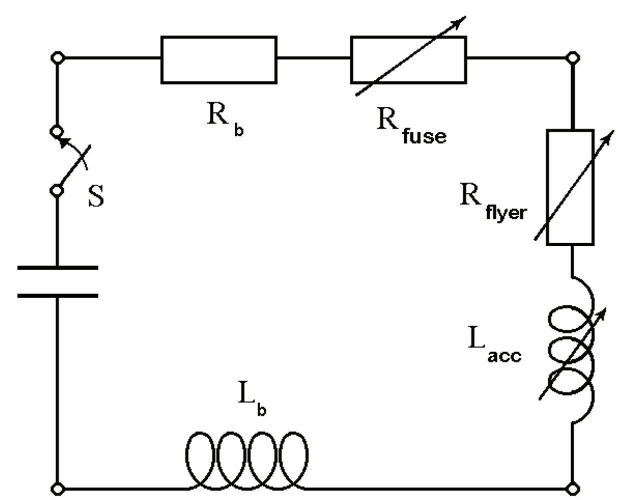

Figure 1 Equivalent electrical circuit of the pulsed power systems used in the two electromagnetic accelerators.

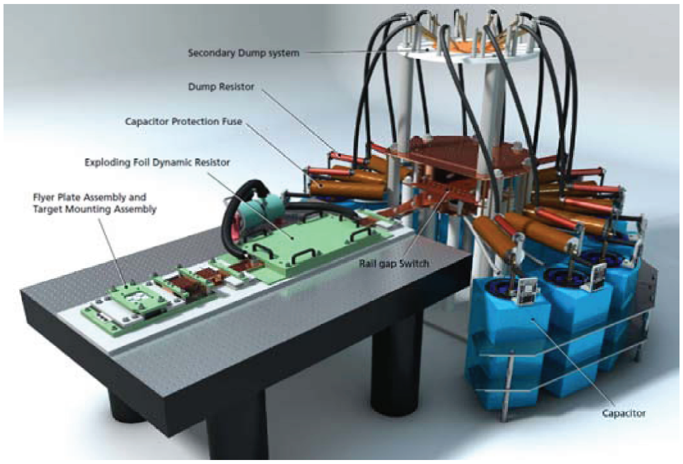

Figure 2 AMPERE facility for accelerating flyer plates installed at AWE Aldermaston, UK.

a) **b)**

Figure 3 QUATTRO facility for accelerating flyer plates installed at Loughborough University
a) Flyer b) QUATTRO bank

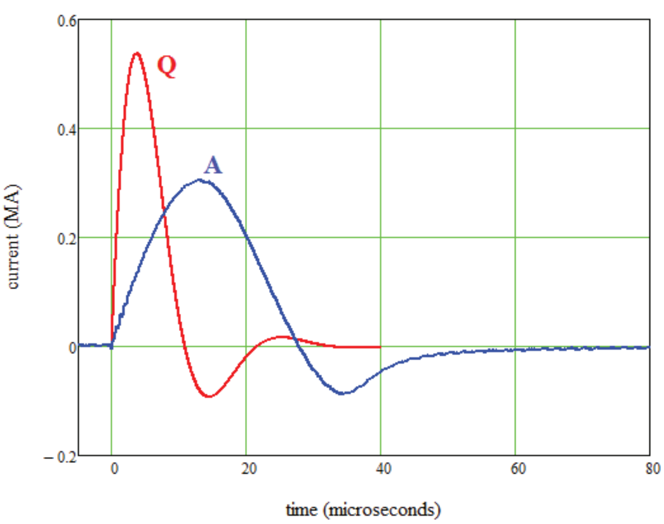

Figure 4 Typical currents produced by AMPERE (A) and Quattro (Q).

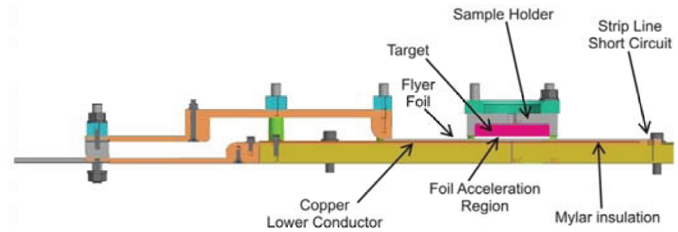

Figure 5 The AMPERE accelerator, part of the parallel-plate transmission strip line.

The electromagnetic accelerator has a simple configuration (Fig. 5), consisting of the following parts:

- a thick metallic part, the 'stator', mounted on the upper part of a heavy support
- mounted above the stator is a thin dielectric layer placed between the flyer and the stator; the initial position of the flyer is determined by its thickness;
- the accelerating 'flyer', positioned above the dielectric layer.

The flyer and the stator are such connected that the same current flows in opposite directions through them generating magnetic fields and therefore a strong repulsive forces. All parts of this accelerator are made as flat as possible avoiding trapped air bubbles between the various components.

3 THEORETICAL MODELLING

3.1 0-D MODEL

The model considers that the current is homogeneously distributed inside all the electromagnetic accelerator metallic components. As a consequence, the following assumptions can also be made:

- the shape of the flyer during its acceleration remains flat during the test and as a consequence there is only one velocity that has to be obtained;
- the deposition of energy and therefore temperature and is also homogenously distributed inside all metallic components with a single temperature being required to be calculated for the flyer and another for the stator.

The equivalent circuit for the system shown in Fig. 1 can be described by the two first-order differential equations:

$$V_0 - \frac{Q(t)}{C} = \left[R_b + R_{fuse}(t) + R_{flyer}(t) + \frac{dL_{acc}}{dt}\right] I(t) + \left[L_b + L_{acc}(t)\right]\frac{dI}{dt} \tag{1}$$

$$I(t) = \frac{dQ}{dt} \quad (2)$$

where C is the bank capacitance initially charged to a voltage V_0. I(t) and Q(t) are the circuit current and the electric charge produced by the discharge of the capacitor into the circuit, R_b is the resistance of the damping resistor and L_b is the self-inductance, excepting the fuse and flyer resistances (R_{fuse} and R_{flyer}) and the accelerator self-inductance L_{acc}, a time-dependent variable. R_{fuse} is obtained using the a model developed in house and the time variation of the accelerator self-inductance is obtained from the 2D magnetic field distribution produced by a parallel transmission line with a homogeneously distributed current flowing through both the flyer and the stator plates. Full details of the calculation are presented elsewhere [1].

Theoretical predictions obtained using the model were compared with the experimental data for which the main AMPERE system parameters are: capacitance 129 µF, initial charging voltage 21.5 kV, bank resistance 8.8 mΩ and bank self-inductance 650 nH. The damping (exploding) aluminium foil is 50 µm thick, 85 mm wide and 300 mm long. The stator is made from 1 mm thick copper sheet, 90 mm wide and 300 mm long and the flyer is manufactured from an aluminium foil with the following dimensions: 300 µm thick, 90 mm wide and 300 mm long. A complete run over 120 µs under Windows 7 on a laptop with an Intel Core i7 CPU @ 2.67 GHz with 4 GB RAM takes just 2 seconds. The most important data, the time dependence of the flyer velocity obtained using the heterodyne velocimetry technique [2], is compared in Fig. 6 with the 0D model prediction. The 0-D model, although simple, can however help in providing a view into the physics and technology of an electromagnetic accelerator being currently used for parametrical investigations during the design of a new machine.

3.2. 2-D MODEL

The 2-D model is based on sophisticated and detailed circuit mesh modeling, for which Loughborough has developed a very reliable technique. Using this technique, the conductors of the transmission line are divided into parallel, isolated filaments as presented in Fig. 7. The circuit mesh network allows an easy application of the Kirchhoff equations to obtain the currents. In this way there are N first-order differential equations that are time-integrated using the initial conditions and a standard integrating MATHCAD subroutine. The results are providing a series of important data: the complete map of magnetic and electric fields, current, force and temperature distributions, the accelerating time-dependent flyer position, etc. Full details of the implementation of this model are provided elsewhere [1]. In the example below, the flyer and the stator are each represented by a total collection of 400 filaments, with 200 independent currents. The total number of differential equations to be integrated in this case is 642. The program is written using MATHCAD 15 and a complete run over 60 µs on a PC operated under Windows 7 with an Intel Core i7 X980 CPU @ 3.33 GHz and with 12 GB RAM takes about a day. As an example, the predicted time variation of the flyer current distribution is shown in Fig. 8 and the corresponding flyer dynamics in Fig. 9.

4 MIDOT PROBE TECHNIQUE

The experimental determination of the current distribution in a transmission line represents a very difficult task. A novel type of inductive probe was recently invented by the two research groups to provide such data.

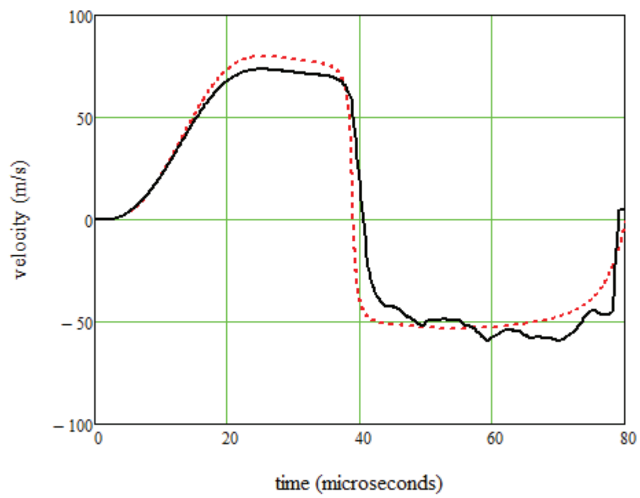

Figure 6 Time dependence of the flyer velocity.
Continuous line: experimental data from heterodyne velocimetry technique.
Dotted line: 0D model.

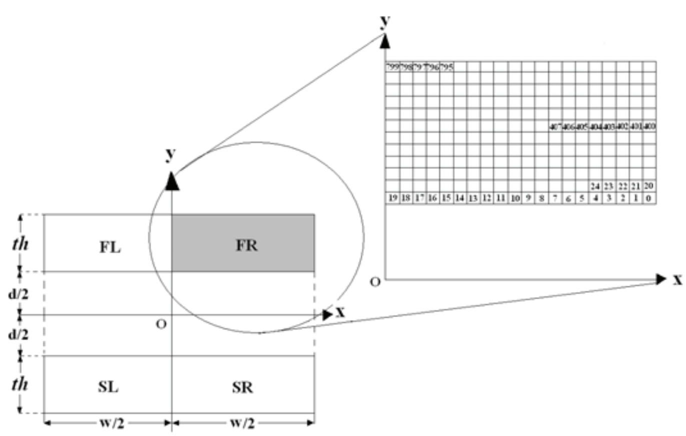

Figure 7 Filamentary representation of the electromagnetic accelerator as a flat transmission line having a width *w* a thickness *t* and a separation between plates *d*. For simplicity, the stator (S) and the flyer (F) are shown here as identical. By symmetry, only currents in one half (left L or R right) have to be calculated.

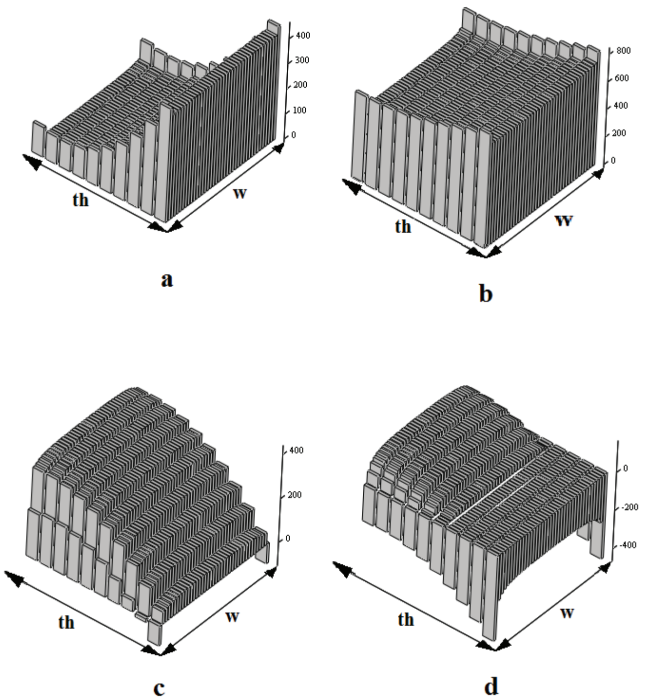

Figure 8 Current distribution inside the flyer at (a) 5 µs, (b) 15 µs, (c) 25 µs and (d) 30 µs, with the vertical scale indicating the filamentary current in Amperes.

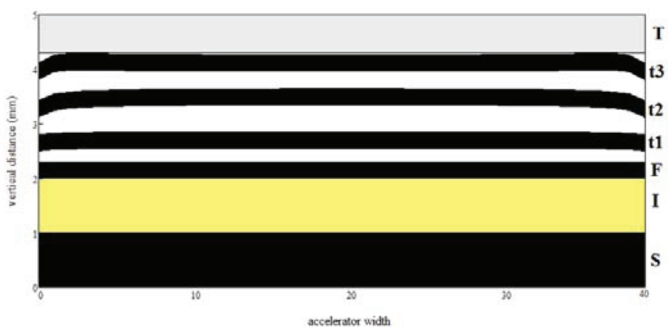

Figure 9 Flyer shape at different moments during the first phase of acceleration: t1=20 µs, t2=30 µs and t3=40 µs
The letters represent: S-stator, I-insulator, F-flyer (initial position), T-target (drawing not to scale).

A preliminary design of such a probe, made from a very thin wire and termed Midot, is shown in Fig. 10. Typical open circuit voltage outputs obtained from two Midot probes during a Quattro flyer experiment are presented in Fig. 11. The mutual inductance between the transmission line (considered as a collection of very thin conductors) and the Midot probe is calculated with great accuracy and the emf generated in the probe's (open) circuit during a test is determined experimentally. The theoretically predicted emf can then be matched to the experimental emf, by empirically adjusting the amount of current flowing through each of the thin conductors forming the transmission line. Although somehow similar to the 2D filamentary model, the calculations do not require any differential equations to be solved and therefore can be performed in a few seconds on any PC. More details about the Midot probes will be presented elsewhere.

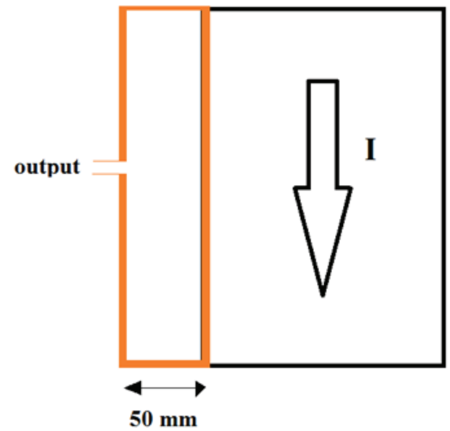

Figure 10 Sketch of a Midot probe installed on top of the Quattro flyer foil electromagnetic accelerator, with its open circuit output on the left hand side. The direction of the flyer current is indicated by an arrow.

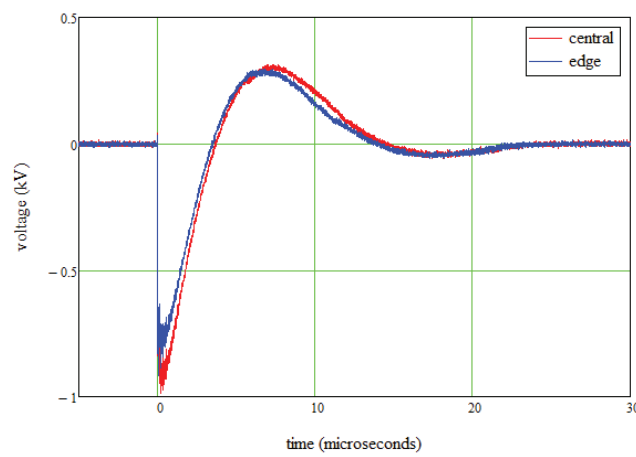

Figure 11 Typical voltage signals from a pair of Midot probes during a Quattro flyer foil test.

5. CONCLUSION

A very successful AWE-LU joint research program produced a wealth of interesting results during its first year with all the tasks successfully accomplished. The activity will continue with refining both the Midot experimental technique and the numerical modeling.

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