# Generating high voltages with a plasma coil transformer


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## Abstract

A novel prototype plasma coil based dry-type transformer has been built and used to create 75kV peak impulse voltages from a 40kVd.c. capacitor bank. This device uses an air-cored coil of exploding wire to produce a high voltage output from a copper magnet wire winding. Effective insulation coordination has been developed for the unique requirements of this device. Preliminary theories behind the mechanisms which drive this device are presented. Future improvements are noted, which are planned to allow voltages of several hundred kilovolts to be generated.


## Introduction

A plasma path, such as a coil, can be created by a wire explosion. The term "Wire Explosion" defines the process in which a wire, when subjected to a large current, undergoes one of several modes of explosion. These can include state changes (i.e. to liquid or gaseous phases), formation of plasma and fragmentation in the solid or liquid state. Current is usually supplied as an impulse of $10^4$ - $10^5$ A from a charged capacitor.

Serious research into the exploding wire (EW) phenomenon began in the 1950s. This primarily focused on explaining the process of explosion and defining the characteristics of any plasma which may have developed. These wire explosions were almost exclusively less than one metre in length, usually using copper, aluminium or occasionally more exotic metals, and impulse voltages of under 20kV [1]. Computer modelling of EW began in the 1970s and continues today as an active area of research [2]. Present applications of EW include plasma and fusion research [3], generation of steep-front shockwaves [4] and various miscellaneous applications such as lightning diverter strips [5].

The University of Canterbury has had an interest in creating straight long distance plasma paths via EW, starting around five years ago. An experimental setup was constructed, using a bank of capacitors as an impulse source, and used for extensive experimentation with wire explosions up to 9 metres long [6]. A 70 metre partial-plasma discharge was also achieved. In the summer of 2007/08, it was realised that EW initiated plasma paths could be formed into coils. Powerful magnetic fields were observed through various experiments, created by the violent impulse currents present.

The plasma coil idea was quickly extended to plasma transformers by adding a secondary winding to the air-cored primary. The rapidly building and collapsing magnetic fields of the primary, when coupled to a secondary with more turns, created high voltages without the need for a very large number of turns or a magnetic core. No magnetically coupled devices that use a plasma/exploding wire coil have been noted in the literature to date. This device represents new possibilities for the range of H.V. test equipment; single-shot extra-high voltages which may be generated using inexpensive and easily constructed equipment.

## The Plasma Transformer

### *Straight Exploding Wires*

The creation of useful plasma paths – straight or coiled – via an exploding wire is not a trivial task. There are many potential outcomes of a wire explosion, based on initial parameters such as wire length, wire diameter and impulse voltage. At present these outcomes are less than predictable, although they are repeatable. Possible explosion outcomes include the following:

- No explosion – not enough energy is transferred to the wire to cause it to break up. Usually all of the capacitor energy is discharged, but as a slow under-damped oscillation – not so useful for rapidly changing magnetic fields.
- Fragmentation – the wire shatters in solid or liquid state due to mechanical vibrations, thermal stress waves, the pinch effect or any number of other mechanisms described and debated in the literature [7]. Usually current is quelled before much energy is dissipated from the capacitors. Fragments are thought to be liquid copper droplets, appearing to be electro-statically charged, allowing them to bounce remarkably.
- Partial Plasma – the wire is vaporised and possibly partially ionised, but the plasma path stops conducting before all of the capacitor energy is discharged.
- Full Plasma – the exploding wire becomes a full plasma path which conducts until there is negligible energy remaining in the capacitors.

The exact parameters required to achieve a desired outcome for a certain length of wire are, at present, obtained solely through experimentation, and interpolation between known parameter sets is not particularly useful. For example, if a wire is not forming a hot enough plasma path, it is not sufficient to assume a larger voltage will necessarily help – in fact this will often lead to a lesser explosion.

An excellent insight can be gained into the mechanism occurring in any given wire explosion through inspection of the voltage and current waveforms. A typical wire explosion (Figure 1) can show an initial current rise as the wire is heated, melted and partially vaporised. The copper vapour is extremely resistive, so current drops away to what is known as the "dwell time". Once the vapour expands enough, it can be ionised, and "re-ignition" occurs, delineated by a second rise in current, discharging remaining capacitor energy.

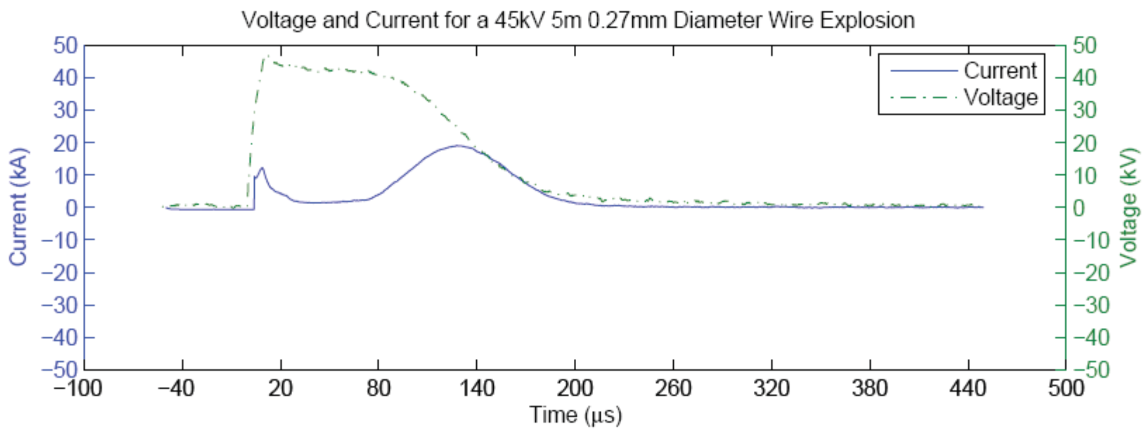


**Figure 1**
**Typical voltage and current waveforms for a full-plasma wire explosion [6].**

### ***The Concept***

A plasma transformer is essentially a two-winding, air cored transformer with an exploding wire as the primary (Figure 2) and dry-type insulation. The secondary winding is wound as a single layer on to a paper-insulated PVC former, a layer of insulation is applied, and finally the exploding primary is wound on the outside. This allows the primary to be replaced after each test, as the secondary is usually still intact. A major design consideration of the plasma transformer is the maximisation of coupling between windings. Inside an air-cored coil, flux density decreases exponentially with distance from the winding (Figure 3), so for maximum coupling the gap between windings must be minimised.

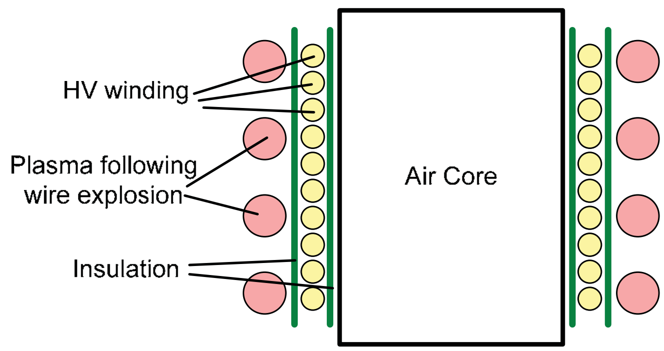


**Figure 2**
**Cross-sectional view of a plasma transformer**

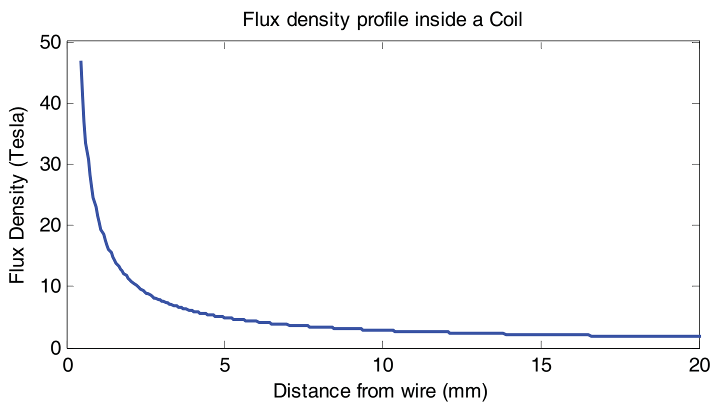


**Figure 3**
**The radial flux density profile inside a single turn, driven by 100kA**

The LV (exploding) winding requires the same careful selection of parameters as straight exploding wires, with the added complexity of the coil shape. Winding diameter and pitch must be coordinated along with wire diameter and impulse voltage. The increased induction of the wire, when formed into a coil, yields a different set of outcomes for any given parameters as compared to a straight wire. It is yet unclear as to what outcome is even desirable; greatest rate of change of current is clearly the goal, but this may occur in the initial current rise, transition to dwell time or re-ignition.

### *Insulation Coordination*

The insulation in a plasma transformer is required in much the same places as a traditional h.v. transformer. However, in the plasma transformer, the challenge of insulation coordination is compounded by conductive gases released from the exploding primary winding and the very close proximity of this to the secondary winding. Around thirty prototype transformers have been wound so far; the main improvements on each prototype were in the insulation coordination.

Inter-turn insulation on the h.v. winding was initially provided by using a large enough winding pitch to avoid flashover. This was proven to be insufficient to prevent turn-to-turn failures (Figure 4), so further dry type insulation was added. The most successful has been Dow Corning 838, a silicone sealant, applied between each secondary turn during winding (seen on the re-opened transformer in Figure 6).

Figure 4
A smudge gives evidence of a turn-to-turn failure occurring on the bottom eight turns of this secondary winding. Note the distortion caused by large short-circuit currents.

Figure 5
The point of a flashover between the primary and secondary windings, through NMN insulation.

*Along the length of the transformer, insulation between windings is provided by a single layer of Nomex-Mylar-Nomex (NMN 5105) insulation paper. This failed frequently while the secondary was referenced to earth (Figure 5*

*Figure 5*), but when the secondary was left floating, it proved to be sufficient. One layer of NMN was also required between the secondary and the PVC former to prevent tracking along the former.

Further problems were encountered with tracking off the ends of the former, causing flashovers through the primary plasma (Figure 6). Either significant quantities of ionised gas had been forced between windings, or over 200kV had been present to cause the tracking. First an end-cap was installed on each end in an attempt to block the gases. A more effective solution was to extend the Dow Corning insulation beyond the ends of the secondary winding by 50mm.

**Figure 6**
**Flashover to the primary plasma short-circuited the secondary winding.**
**Tracking is seen at the top and bottom of the winding, indicated by red circles.**

The primary winding presents a unique insulation challenge. Although sufficient winding pitch can easily be attained to insulate against the 40kV impulses used, explosively expanding hot plasma causes turn-to-turn failure very early in the impulse. This can be very easily identified in long-exposure photos as extra-bright plasma between turns, with the remainder of the wire not turning to full plasma (Figure 7). A much larger winding pitch of around 50mm can prevent this from occurring, but this increases the radial component of the magnetic field to the detriment of the axial (coupling) component (Figure 8). A better solution is the use of a gas shield – a PVC helical baffle which can be fitted to the primary winding to segregate the plasma turns (Figure 9). As noted with straight exploding wire, fragments are liquid copper droplets with elastic "bounce" properties. This is significant for the longevity of the baffle, as most polluting particulate matter is self-ejecting.

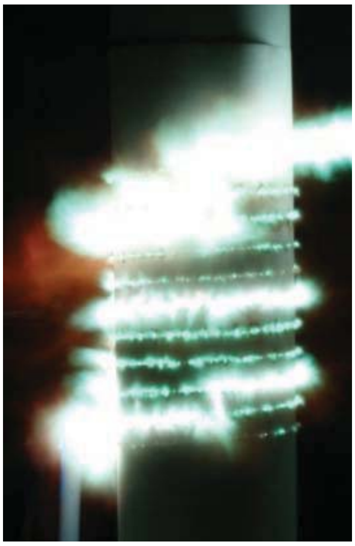

Figure 7
Turn-to-turn failures in several places on the 10-turn primary winding.

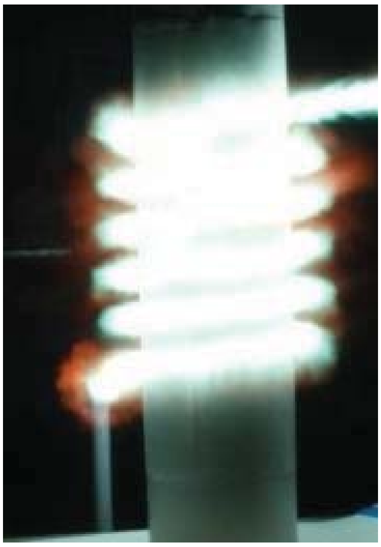

Figure 8
No flashover occurs due to the increased winding pitch on a 5-turn primary winding.

Figure 9
Plasma is effectively retained on a 10-turn winding when the helical baffle is in place.

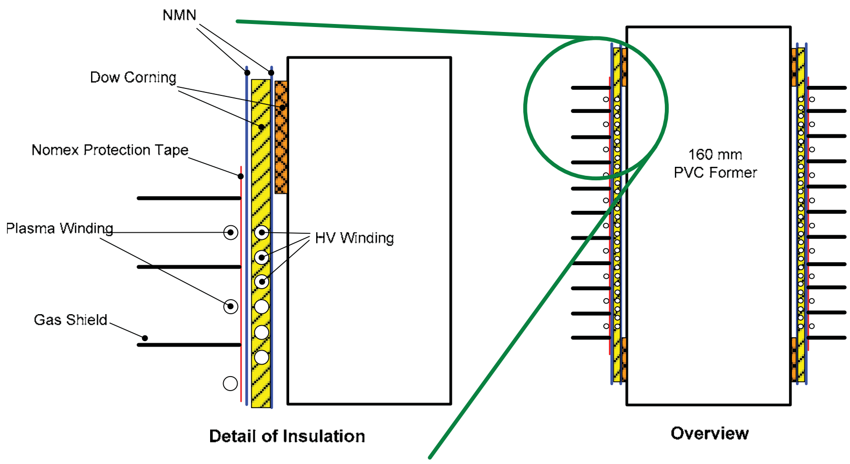


**Figure 10**
**The complete insulation design of a plasma transformer**

### *Measurement*

Due to the high voltage, high current and noisy environment intrinsic to wire explosion experiments, even simple measurements can become complicated. At present, the forms of measurement used are plasma coil voltage, h.v. winding voltage, plasma coil current and photography.

The plasma coil and h.v. winding voltages can be measured via a capacitive voltage divider (CVD). While this has been a very successful method for measuring plasma coil voltage, measurements of the h.v. winding voltage have proved somewhat dubious. The CVD seems to adversely affect the peak voltage reached by the h.v. winding, possibly due to the capacitive loading or resonance with the winding. The CVD capacitance is 200pF.

Plasma coil current measurement requires purpose-built equipment. Commercial current clamps can not be used, as they are not rated for the huge rates of change of current, which can reach 10GA/s [6]. They usually contain steel or ferrite cores, which saturate at much lower flux levels. Instead, a Rogowski Coil must be used. This is an air-cored device which encloses the azimuthal flux of a conductor with a coil of exact known properties. The output voltage of the coil is proportional to the rate of change of current, so must be integrated to obtain a current waveform. A Rogowski coil is not available at present, so no current waveforms have yet been obtained for plasma transformers

Photographs of an exploding wire are obtained through three methods. The first, which was used to obtain all plasma photographs in this paper, is long exposure. The camera's shutter is held open for the entire duration of the experiment (i.e. all light emitted appears in the same photograph). This guarantees that nothing will be missed, but any chronology information is lost. The other two methods are short exposure and high-speed video. Both of these allow a specific event in a sequence to be captured individually, but are much more complex to set up.

### *The Working Model*

Described below is the exact setup which allowed a peak voltage of 75kV to be generated with a plasma transformer. A complete list of transformer specifications can be found in Table 1. The insulation was constructed as shown in Figure 10 above. A calibrated spark gap was placed across the output (secondary) terminals of the transformer, and was photographed flashing over during the experiment, indicating a successful result (Figure 11).

Identical experiments were performed with the spark gap set to different voltages and also a CVD along with the spark gap. The sphere gap flashed over when calibrated to 59kV and 75kV, but failed to trigger at 85kV or 110kV. The photos showing flashovers of the spheres contain evidence of multiple strokes across the sphere gap.

The authors of this paper are excited by the fact that greater than 75kV can be created with only 25 metres of 0.335mm magnet wire, in a single layer h.v. winding of only 50 turns. We find a dry-type and air-cored transformer than produces 1.5kV per turn a most interesting achievement.

| | | |
|---|---|---|
| **Primary Winding** | Coil Diameter | 162 mm |
| | Coil Height | 250 mm |
| | Wire Diameter | 0.270 mm |
| | Number of Turns | 10 |
| | Pitch | 25 mm |
| **Secondary Winding** | Coil Diameter | 160 mm |
| | Coil Height | 250 mm |
| | Wire Diameter | 0.335 mm |
| | Number of Turns | 50 |
| | Pitch | 5 mm |
| **Impulse Generator** | Charge Voltage | 40 kV DC |
| | Total Capacitance | 21.4 µF |

**Table 1**
**Specifications of a plasma transformer capable of an output of at least 75kV**

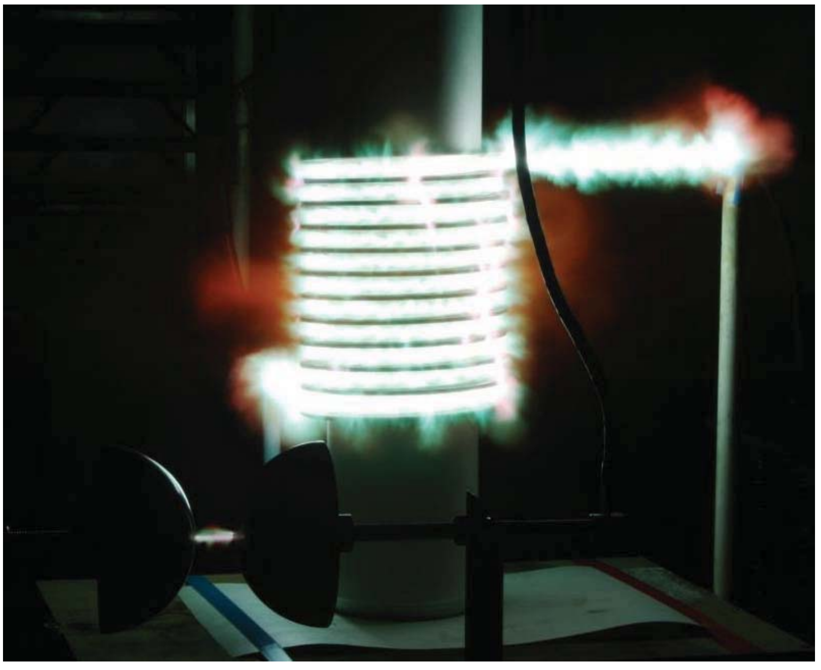

**Figure 11**
**A successful test of the 75kV plasma transformer.**
**Note the sphere gap in the bottom left of the photo has flashed over**

## Future Work

The target of this work is to create e.h.v – up to hundreds of kilovolts. The output voltage from the plasma transformer can be maximised once the mechanism producing time-varying primary current is better understood. This requires further study of straight exploding wire, such that the fastest increase or shut-down of current can be achieved. This will likely be done by either improving the vaporisation mechanism (a faster transition to the dwell time), or a more violent re-ignition. Also, the secondary winding pitch of 5mm could be reduced down to a little as 1 mm, producing an estimated 375kV – and this is before multiple layers are even considered. Once a mechanism for greatest output voltage is obtained, the insulation of the plasma transformer may be further improved to contain the voltages generated.

Extensions of the prototype single-shot plasma transformer are pulsing and steady-state versions. The pulsing version will attempt to re-use the plasma path several times with current impulses. A steady-state version may be possible via the use of the pinch-effect or similar; a mechanism which allows the magnetic containment of hot plasma. Then an a.c. current can be passed through the coil, generating a continuous a.c. output from the transformer.

## Conclusions

A prototype plasma transformer has been developed and was successful in producing a 75kV peak voltage on the h.v. side from a 40kV impulse applied to the plasma side. The 75kV has been generated without the use of any core material or transformer oil. The h.v. conductors are simply wound only on a plastic former in a helical manner. The h.v. winding is 50 turns, using only 25m of 0.335mm magnet wire. Through many experiments, a dry-type insulation system has been designed which effectively contains the plasma associated voltages.

The plasma coils have proven to be intrinsically different from the straight exploding wires to which the authors have recently become accustomed. While the theories and knowledge of straight exploding wires is transferable to the coiled equivalents, a new set of operating parameters needs to be found in order to maximise output voltage. Many avenues of design improvements have been identified which are planned to lead to achievements of extra-high voltages.

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## Biographies

**Rowan Sinton** completed his B.E. degree in electrical and electronic engineering in 2007 at the University of Canterbury, Christchurch, New Zealand. He is currently pursuing the Ph.D. degree at the University of Canterbury. His research interests are applications of High Voltage and novel electrical machinery.

**Campbell Ross Hammond** works for Genesis Energy as an Electrical Engineer and is interested in high voltage asset maintenance and testing. Campbell obtained a NZCE (Industrial Measurement and Control) from the Waikato Institute of Technology in 2001. He then completed parallel Trade qualifications in Industrial Control & Instrumentation and Electrical Engineering. Campbell continued in Tertiary Education and completed a BE (Hons) degree in electrical and electronic engineering from the University of Canterbury in 2008.

**Dr Wade Enright** is a senior lecturer at the University of Canterbury. He also offers electrical engineering services to the industry via his own company "Viva." This company is in its $10^{th}$ year of business. Wade specialises in power transformers and high voltage. Wade has worked for the Electricity Corporation of New Zealand Ltd in their technical specialist group. During 1996 he worked for the Manitoba HVdc Research Centre in Winnipeg, Canada. He completed his BE (Hons) and PhD degrees in electrical and electronic engineering from the University of Canterbury in 1992 and 1995 respectively.

**Professor Patrick S. Bodger** is now Head of the Power Group within the Department of Electrical and Computer Engineering, University of Canterbury, New Zealand. He is also Director of the Electric Power Engineering Centre. From 1977-1981 Professor Bodger worked for Electricity Division, Ministry of Energy, New Zealand. Professor Bodger completed his B.E. (Hons) and PhD degrees in Electrical Engineering from the University of Canterbury in 1972 and 1977 respectively.