The Role of Mass Distribution in the Demonstration of Ampèrian Longitudinal Electrodynamic Forces

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Introduction

In general, physicists and engineers predict the motion of an object by applying known force laws and calculating the net force and impulse acting on it. With knowledge of the mass of the object, Newton's second law of motion yields a value for its acceleration. However, for impulses of large force but short duration, the acceleration may be too fast to be measured and thus it is often easier to just record the object's maximum velocity. One must however be very careful in the consequent dynamical analysis because unlike its acceleration, the velocity acquired by a test object depends not just on its mass, but also on the mass of the equipment on which the reaction force is impressed.

Take the example of two repelling electromagnets resting on separate gliders on a fairly frictionless air-track of the kind found in school physics labs. Let us call the two gliders **A** and **B,** and pay particular attention to the motion of **A** with respect to the lab bench. If the gliders are initially close to each other and if both electromagnets are given a current pulse for a finite time, then we find that not only does the maximum velocity of **A** depend on its own mass but also on the mass of **B**. This occurs because the magnetic force between them is a Newtonian inverse square force which decreases with distance of separation. If **B** is very light, then it will initially accelerate more quickly and the integral of the distance dependent force acting over a finite time period will be weaker than if **B** was heavier. This means that a lighter **B** results in less impulse and as a result both gliders acquire less momentum. As a consequence it must be remembered throughout this paper that the final velocity of an object subjected to a Newtonian impulsive force is not just dependent upon its own mass, but also the mass of the object causing the force.

This fact will seem very obvious to a mechanical engineer. However it is a principle that has been forgotten in the subject of electrodynamics, particularly with regard to macroscopic electrical circuits. The primary cause of the separation between electrodynamics and Newtonian dynamics has been the adoption of the presently favoured Lorentz force law and its required supporting theory, Einstein's Special Relativity (SR).

In his eloquent description of (SR) relativistic dynamics, the MIT professor A.P French stated [1]:

> "Even if the force on an object is known to be solely due to the presence of some other object, we have no unique way of describing their *mutual* interaction; we can only describe the force exerted on either body, separately, at some given point in space-time. … What the relativistic analysis does do, however, is to compel us to conclude that, according to measurements in a given inertial frame, the forces of action and reaction are in general *not* equal and opposite, and so the total momentum of the interacting particles is not conserved instant by instant. This fact leads, if one wishes to hold to conservation of momentum, to the idea that momentum (as well as energy) may

reside in the field that describes the interaction of separated particles." (italics are from A.P. French)

With the present schism between relativistic and Newtonian mechanics as described by French, one should hopefully be able to distinguish which is correct by experiment. In 2001, this author along with T. Phipps Jr. and D. Roscoe published the results and analysis of an experiment which demonstrated the existence and strength of longitudinal electrodynamic forces which are predicted by Ampère's force law [2]. This will be described as the GPR experiment. The results of this experiment can only be understood by an analysis which involves mutual simultaneous interactions between current elements based on Newtonian mechanics.

A few years later, comments were published in the same journal by A.E. Robson [3], highlighting a possible alternative explanation of the results which had not been specifically excluded in the GPR paper [2]. The experiment reported here was conceived as a response to these published comments.

The primary objective of the recent experiment is to demonstrate that knowledge of the total force on a mobile section of a circuit is not sufficient to predict its maximum velocity as a result of a current pulse. It has now been shown conclusively that the mass distribution of the remainder of the circuit is of fundamental importance in determining the motion of a mobile section of the conducting circuit. This demonstration of direct matter interaction between remote parts of a circuit reveals the necessity of Newtonian action at a distance forces. A (SR) relativistic explanation is not possible because the Lorentz force cannot describe where in the circuit the reaction force is felt. The Ampère force law is the only known action at a distance electrodynamic force law that obeys Newton's third law and is therefore the only candidate explanation considered here.

The GPR Experiment

A schematic of the experimental circuit described in [2] is presented in figure 1. The current is fed into the system in the figure by a coaxial cable shown at the top. The other end of this cable is connected to a high voltage capacitor bank and a switch. In figure 1 the current passes through the central electrode to the "Top Gap" where it is forced to form an arc to the "Armature". Another arc forms in the "Bottom Gap" which then allows the current to flow into the lower central electrode and back to the sheath of the coaxial cable via the base and top plate and the six cylindrically symmetric outer legs.

The "Armature" consisted of a 45 mm length of 1/4" diameter copper rod with 3/16" diameter tungsten rod inserts extending 5 mm from either end of the copper rod. This gave a total armature length of 55 mm and weighed 17.7 gm. To ensure that the arc current passed entirely through the end faces of the tungsten electrodes, the sides of the electrodes were insulated with a ceramic coating. This precaution enabled us to more accurately model the current as consisting of longitudinal streamlines in the metal electrodes near the arc gap regions. The ceramic was also applied to the sides of the upper and lower stationary electrodes which were made from the same 3/16" diameter tungsten rod. The armature was coaxially supported in the 75 mm gap between the upper and lower stationary electrode. This ensured that the sum of the top and bottom arc lengths were always 20 mm. The armature was prevented from moving laterally by passing through a 8 mm hole in a rigidly held plastic plate. Attached to this plate were two thin steel leaf springs which were bent slightly upward and gripped the armature as shown in figure 1. This arrangement provided only a small resistance to upward motion, but created a very large resistance to downward motion. The springs therefore allow the armature to be thrown upward during the discharge and then prevent it from falling back down again, allowing the maximum height gained to be measured. The armature could be positioned before the discharge so that there was a predetermined bottom gap length.

The experiment demonstrated that if the length of the bottom gap was shorter than the top gap and the current pulse was sufficient then the armature was found to have moved to a higher position. An upward impulsive force will cause the armature to rise a distance, h. By measuring h, the initial momentum, mv_i, of the armature can be calculated by equating the initial kinetic energy of the armature ($mv_i^2/2$) to the potential energy (mgh) it has gained at the top of its rise where g is the acceleration due to gravity. The initial momentum must be caused by an impulse which can be represented by $\int F\,dt$ where F is the upward force.

$$\int F\,dt = mv_i = m\sqrt{2gh} \quad . \tag{1}$$

In [2] it was deduced that the cause of the upward force on the armature could not be of mechanical or electrostatic origin, leaving only the possibility of an electrodynamic force mechanism. The fact that the force acted in the same direction as the current streamlines ruled out the possibility that the Lorentz force law could explain this result since it predicts a force which is purely perpendicular to the current with no longitudinal component. Therefore Ampère’s force law was applied to the circuit geometry to determine the magnitude of the predicted force.

The details of the experiment and calculation are given in detail in the original publication [2], but for the purposes of the present paper, the methodology of the calculation is of great importance.

Ampère created a law between two current elements, which he defined as a small lengths of wire ($d\ell$), passing a certain amount of current, *i*. Since current does not actually flow in infinitely thin filaments, P. Graneau and this author [4] have slightly modified Ampère's definition to a cubic volume current element which can still be defined by a length dimension and the current passing through it. The Ampère force between two such elements $i_m dm$ and $i_n dn$ can be expressed as:

$$\Delta F_{m,n} = -\frac{\mu_0}{4\pi}\frac{i_m dm\, i_n dn}{r_{m,n}^2} f(\alpha,\beta) \quad , \tag{2}$$

where $r_{m,n}$ is the distance between the centres of the two elements and α and β are the angles that the current elements make with the vector that joins them. A positive force represents repulsion. $f(\alpha,\beta)$ is a purely geometrical and dimensionless function that was the pinnacle of Ampère's empirical discoveries. [5]

$$f(\alpha,\beta) = 2\cos(\beta-\alpha) - 3\cos\alpha\cos\beta \quad . \tag{3}$$

In order to predict the net force on an element, one must perform a summation in which all of the elements in the circuit are allowed to interact with it. It was well known to Ampère [5] and others [6-8] that the net longitudinal force component acting on an element as a consequence of interaction with the rest of its own circuit is identically zero. Further the predicted transverse force component which is perpendicular to the current direction is equal to that predicted by the Lorentz force law. This has led many people including the authors of [6-8] to claim that the Ampère and Lorentz force laws are equivalent and thus neither predict a longitudinal force. This is however a grave misconception that ignores the quite distinct mechanics that underlie the two laws and highlights an over reliance on mathematics rather than experiment.

The Ampère force law does not require the existence of an electromagnetic field because, unlike the relativistic (SR) Lorentz law, the force between every pair of elements necessarily obeys Newton's third law. Consequently, one can examine an experimental problem as a mechanical engineer would proceed. It is often more useful to discover the force between two objects rather than calculating the force on something with disregard as to what causes it. For example, an atom in the middle of a straight wire may have zero net longitudinal force acting on it, but this tells nothing of whether the wire is in tension and likely to break. In this case, it is far more useful to calculate the Newtonian equal and opposite forces between two sections of the wire to investigate the stress across an interface and thus discover whether the wire will break or not. In a similar manner, by calculating the forces across obvious interfaces, one can examine the circuit in the GPR experiment to reveal a prediction of longitudinal motion based on the Ampère force law and Newtonian mechanics.

For this analysis, we must remember the example given in the introduction of the two frictionless pulsed electromagnets. For a given current pulse in both magnets, the final velocity of one of them with respect to the lab depends on the mass of the other. Similarly, the final velocity that a current element receives as a result of an impulsive Ampère force interaction also depends on the mass of the element with which it interacts. Secondly, it is important to remember that the Ampère force law (eq.(2)) is a Newtonian inverse square law and as a consequence the largest forces are impressed between nearby elements.

In reference [2], the GPR experiment was analysed in a section by section manner. The primary objects were the 17.7 gm armature, the plasma in the top and bottom gaps and the remainder of the circuit which was heavy and firmly fixed to the earth. As a result of the large density discrepancy between metal and plasma, the predicted Ampère forces have differing effects on the overall acceleration of the armature as a result of Newtonian mechanics. Such an analysis cannot be performed with the Lorentz force law as it is impossible to identify the location and distribution of the reaction forces on the rest of the circuit.

- **armature - armature interactions**: Since the forces between current elements are Newtonian, interactions between elements in the same rigid body cancel each other and are incapable of moving the body.

- **armature - plasma interactions**: Very strong Ampère forces occur between the metallic current elements at the end of the armature and the adjacent plasma in both the top and bottom arc gaps. However the metal electrodes are approximately 3 to 4 orders of magnitude more dense than the arc plasma. This means that there is roughly 3 to 4 orders of magnitude times as much force acting on a plasma atom than on an atom of comparable mass in the metal lattice. The acceleration of the plasma is consequently several thousand times faster than if the plasma had the density of a solid. Therefore the repulsion between plasma and armature decreases extremely rapidly over time. As a result, only a negligible amount of momentum is given to the armature and we can neglect these interactions in the calculation of armature velocity. This is analogous to the case of the two magnets described in the introduction when one is very light compared to the other. It is difficult to apply accurate numbers to this approximation since we do not know the actual plasma density, nor the rate at which fresh atoms are fed into the plasma-metal interface. Nevertheless, there is a solid semi-quantitative case for ignoring the armature-plasma interactions when calculating the measurable armature velocity.

- **armature - fixed circuit interactions**: Interactions between elements in the fixed circuit and those in the armature result only in acceleration of the armature since the fixed circuit is rigidly connected to the earth and therefore has an almost infinite mass compared to the armature. The finite time period of a pulsed discharge causes a predictable final velocity which can be measured by the height gain method described by eq.(1).

These Newtonian considerations demonstrate that the only interactions that can produce a significant acceleration of the armature are those between elements in the armature and those in the fixed circuit. Data from the GPR experiment [2] indicates that the armature can only have moved less than 100 μm relative to the fixed circuit during the 140 μs current pulse and therefore the force can be considered to be simply a function of the instantaneous current. The calculated net impulse on the armature due to the fixed circuit will then give the expected maximum velocity relative to the lab.

One can calculate the net force on each current element in the armature due to interaction with only the elements in the fixed circuit using eqs.(2) and (3) and in general will find a non zero force with a longitudinal component. If one then sums these forces acting on all of the elements in the armature one can calculate a figure for the total effective longitudinal force acting on it. This can be represented by a dimensionless constant, *k*.

$$F_{arm} = \frac{\mu_0}{4\pi} k\, i^2 \tag{4}$$

By the mathematics involved in summing Ampère's formula over the entire fixed circuit, it turns out that the values of the longitudinal force and *k*, do not depend on the shape of the fixed circuit but only on the length of the two arc gaps. If both gaps are of equal length, there is no net longitudinal force acting between the armature and the fixed circuit. In general, the direction of the effective longitudinal force is away from the shorter gap. Since the diagnostic measurement system in the GPR experiment was designed to only measure upward motion, all of the experiments had an initial bottom gap shorter than the top gap.

Using eqs.(1) and (4), *k* could be measured for each experimental shot.

$$k = \frac{m\sqrt{2gh}}{\frac{\mu_0}{4\pi}\int i^2\, dt} \quad , \tag{5}$$

where *m* is the mass of the armature, *h* is the measured height gain as a result of the current discharge, *g* is the acceleration due to gravity, μ_0 is the constant known as the permeability of free space and i is the instantaneous current measured by a current transformer. In reference [2], a graphical comparison of theoretical and experimental values of k was plotted against the length of the bottom gap. A similar reproduction of the data is presented in figure 2. The fact that many of the experimental points lay below the theoretical curve was discussed in [2] and was primarily due to the small and slightly variable friction between the armature and the supporting leaf springs. A future version of the experiment should involve high speed photography and an armature suspension system with no friction to eliminate this source of error. Nevertheless there is good agreement between the measured force and the Ampère prediction. Importantly, the force is a maximum at zero bottom gap and goes to zero at equal top and bottom gaps as predicted.

The Variable Mass Electrode Experiment

Since the publication of the GPR experiment [2], the only critical commentary to have been published was from A.E. Robson [3]. He based his discussion on the apparent mathematical equivalence of the Ampère and Lorentz force laws and was not convinced by our arguments repeated above that highlight the differing mechanics on which the two laws are founded and so allow the Ampère force law to make a prediction of longitudinal motion. Based on his conviction that longitudinal electrodynamic forces could not exist, he conjectured a qualitative model which he claimed could explain the observed motion based on mechanical forces due to the arc explosions.

It was felt that these comments could best be answered with further experimental information to support the mechanical arguments given in the present paper. The following experiment demonstrates clearly that the armature motion (a) is a result of electrodynamic forces and (b) depends highly on the mass distribution of the rest of the circuit.

A similar experimental arrangement to the one shown in figure 1 was used. Since the Ampère calculations as well as Robson's proposed alternative mechanisms only depend on the initial arrangement of the arc electrodes and the armature, this part of the set-up is all that needs to be described for the analysis of the recent experiment. Three electrode armature configurations were used and are shown schematically in figure 3 and photographically in figure 4. In all of these cases, the upper electrode, the armature and the armature supporting structure and springs were identical to the GPR experiment [2]. In figure 4 it can be seen that the surface of the upper electrode becomes pointed due to melting after several shots. Occasionally, this was filed flat and it made no difference to the results. In these experiments, the armature weighed 16.8 gm. The only difference between these electrodes and those in the GPR experiment was that the insulation covering the side surfaces of the arc electrodes was made more durable, employing Nylon rings instead of the more fragile ceramic. In all of these experiments, the top gap was 13.5 mm long. The three initial conditions are described below.

a) In the 38 mm long region between the lower part of the fixed circuit and the armature, we inserted a type (a) stainless steel electrode, supported from directly beneath by a 12 mm long, 0.5mm diameter Aluminium wire. The electrode was 25 mm long and had a 2 mm thick Nylon insulating ring around the top which had the effect of forcing the current to pass through the 5 mm diameter flat end surface. The type (a) electrode had the same mass as the armature, 16.8 gm. The electrode was therefore only supported by the small amount of stiffness in the 0.5 mm diameter wire. In the initial arrangement before each shot, the type (a) electrode was in direct contact with the bottom of the armature. The action integral ($\int i^2 dt$) required to evaporate an aluminium wire is 7.30×10^{16} (A^2s/m^4) [9]. For the 0.5 mm diameter wire, this requires the passage of electric current with an action integral 2814 A^2s. In the discharges reported here, this action integral was passed in 4 μs, leaving the type (a) electrode floating, unsupported, during most of the current pulse which lasts for around 200μs.

b) The type (b) electrode served the same role as the type (a) but was of much lower mass. It was also made of 5 mm diameter stainless steel rod and had a Nylon insulating ring around its top surface. However it was only 5 mm long and weighed just 0.85 gm. In all type (b) shots, the electrode's initial position was in direct contact with the bottom surface of the armature and it was supported from below by a 32 mm length of 0.5 mm diameter Aluminium wire. As in the type (a) shots, the Aluminium wire was rapidly vaporised, leaving the type (b) electrode unsupported during most of the current pulse.

c) There was no lower electrode and the lower gap was simply crossed by a 38 mm long, 0.5 mm diameter Aluminium wire which made direct contact with the bottom surface of the armature.

For the results presented here, we used a 10.2 μF capacitor bank and the entire circuit had an inductance of 2.7 μH. With an initial capacitor voltage of around 25 kV, the current pulse was a damped ringing discharge with a first current maximum of around 41 kA and a ringing frequency of around 30 kHz. The discharge had a duration of roughly 200 μs. Electrodynamic forces are proportional to the square of the current, and thus discharges that produce equal impulses should have equal action integrals which is defined as the square of the current integrated over the duration of the discharge. In order to achieve this, the initial capacitor voltages were varied from one condition to another. This was required as a consequence of the initial slightly higher electrical resistance of the longer lengths of 0.5 mm diameter Aluminium wire used in the type (b) and (c) tests. The average parameters for each condition and the experimental measurements of h are given in Table 1. The value of the armature initial velocity, v_0, is calculated from h using eq. (1).

The type (a) and (b) shots were taken alternately, with the type (c) shots performed before and after the series as a control test. The type (a) and (b) shots are shown graphically in the order in which they were performed in figure 5. The third type (a) shot was found to have completely crossed the arc gap and collided and stuck to the top electrode, thus the height measurement is certainly lower than would have occurred without obstruction. Consequently, it is important to bear in mind that the average of the type (a) shots is an underestimation of the true height gain and initial velocity estimate. The repeatable contrast in height measurement between the type (a) and type (b) shots demonstrates conclusively that the mass of the lower electrode has a very significant effect on the motion of the armature.

In order to make a quantitative prediction for the outcome of these tests, one can start with the fact that the type (c) tests produced no armature acceleration. This means that the armature is sufficiently far from the fixed circuit to not receive any measurable acceleration from interactions with it. Therefore, we shall examine simply the ramifications of the interaction of the unsupported type (a) and (b) lower electrode and the armature.

An Ampère force calculation was performed to investigate the repulsion between two 5×5 mm square cross section conductors, one with a length of 55 mm representing the armature and the other taking on the lengths between 1 and 55 mm including the lengths 25 and 5 mm representing the type (a) and (b) lower electrodes respectively. The lower mass, type (b) electrode (0.85 gm), must have acquired the same momentum as the armature which averaged 3.5×10^{-3} kg m/s for the type (b) shots using data from table 1. This yields a maximum relative velocity of 4.3 m/s, demonstrating that the electrodes separate by less than 1 mm during the 200 μs current pulse. The computer modelling has shown that this slight change in geometry actually causes a 10% increase in the force constant, k, which is shown in figure 7. For our purposes here we nevertheless considered k to be a constant throughout the discharge. The geometry changes less during the discharges involving the heavier type (a) electrode. The reason that the repulsion force initially increases as the electrodes separate is due to the fact that the Ampère force predicts attraction between some pairs of elements on opposite outer edges of the respective electrodes when the angle between the current direction and the line joining them exceeds 35.3º. These attractions become less significant as the electrodes separate further.

In calculations involving at least 625 current filaments, the longitudinal force constant, k, between the lower electrode and the armature was calculated and the results are displayed in figure 6. Using eq.(5), a k value could be calculated for the type (a) and (b) data in table 1. These experimental results are also shown on figure 6 and demonstrate good agreement with the theoretical calculation, lending further confidence to the Ampère model.

Discussion

In the comments published by Robson [3], he described two separate mechanisms to explain the armature motion in the GPR [2] experiment. He claimed that when there was an arc underneath the armature, then the explosive mechanical force of the very low mass plasma was sufficient to accelerate the armature upward. He argued that the shorter arc in the bottom gap had more effect on the armature than the longer and less confined arc in the top gap. He recognized that the GPR paper had anticipated this argument and as a result had specifically demonstrated that the upward armature motion was in fact a maximum when there was no arc in the bottom gap when the electrodes were initially in contact. For this situation, Robson devised another mechanism to explain the armature motion. He argued that the arc in the top gap, pushed down on the armature which consequently "bounced" elastically off the heavy fixed circuit below it and moved upward. The experiment described in this paper however demonstrates that the armature moves upward even when only touching a very light electrode such as in the type (b) experiments. The 16.8 gm armature certainly cannot bounce off a freely floating 0.85 gm lower electrode. In this experiment, all of the arcs are long and therefore unconfined. As a consequence, neither of Robson's mechanisms can explain the behaviour of the recent experiments described here. Therefore we are justified to retain the conclusions stated in [2] that longitudinal electrodynamic forces do exist and can be predicted quantitatively. Furthermore, the numerical agreement between theory and experiment justifies our qualified assumption that the armature-plasma interactions do not noticeably affect the armature velocity.

The most important conclusion to be drawn from this experiment is that the shape of the circuit and the magnitude of the current pulse are not sufficient to predict the dynamic effects due to electrodynamic forces. We have shown that the motion of a part of the circuit very much depends not only on its own mass but also on the mass distribution of the circuit. This behaviour implies direct interactions between separated parts of the circuit and requires an electrodynamic force law that obeys Newton's third law between current elements at all times. Ampère's law, not only has these qualitative properties but has been shown to quantitatively agree with all electrodynamic force experiments [4] including GPR [2] and the one reported here.

Relativistic mechanics and the Lorentz law can only describe the interaction between the field and the conductor and therefore the motion of an armature cannot depend on the mass distribution of the circuit. Further, the Lorentz force always acts purely perpendicular to the current streamlines in a conductor and therefore cannot explain the observed longitudinal repulsion between the lower electrode and the armature. This experiment therefore demonstrates conclusively that the Lorentz force does not represent reality.

In summation, longitudinal electrodynamic forces do exist and can cause motion in the direction of current flow. These forces are predicted by Ampère's force law which has been found to be the most accurate model of all existing electrodynamic force laws when applied in the Newtonian framework in which it was conceived.

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Type	$mass_{electrode}$ (gm)	V_0 (kV)	I_{max} (kA)	$\int i^2 dt$ (A^2s)	h (mm)	v_0 (m/s)	k
a	16.8	25	41.6	47900	11.7	0.48	1.68
b	0.85	27	42.4	47600	2.2	0.208	0.73
c	0	27	43.3	46800	0.0	0.0	0.0

Table 1 : Data from variable electrode mass experiment

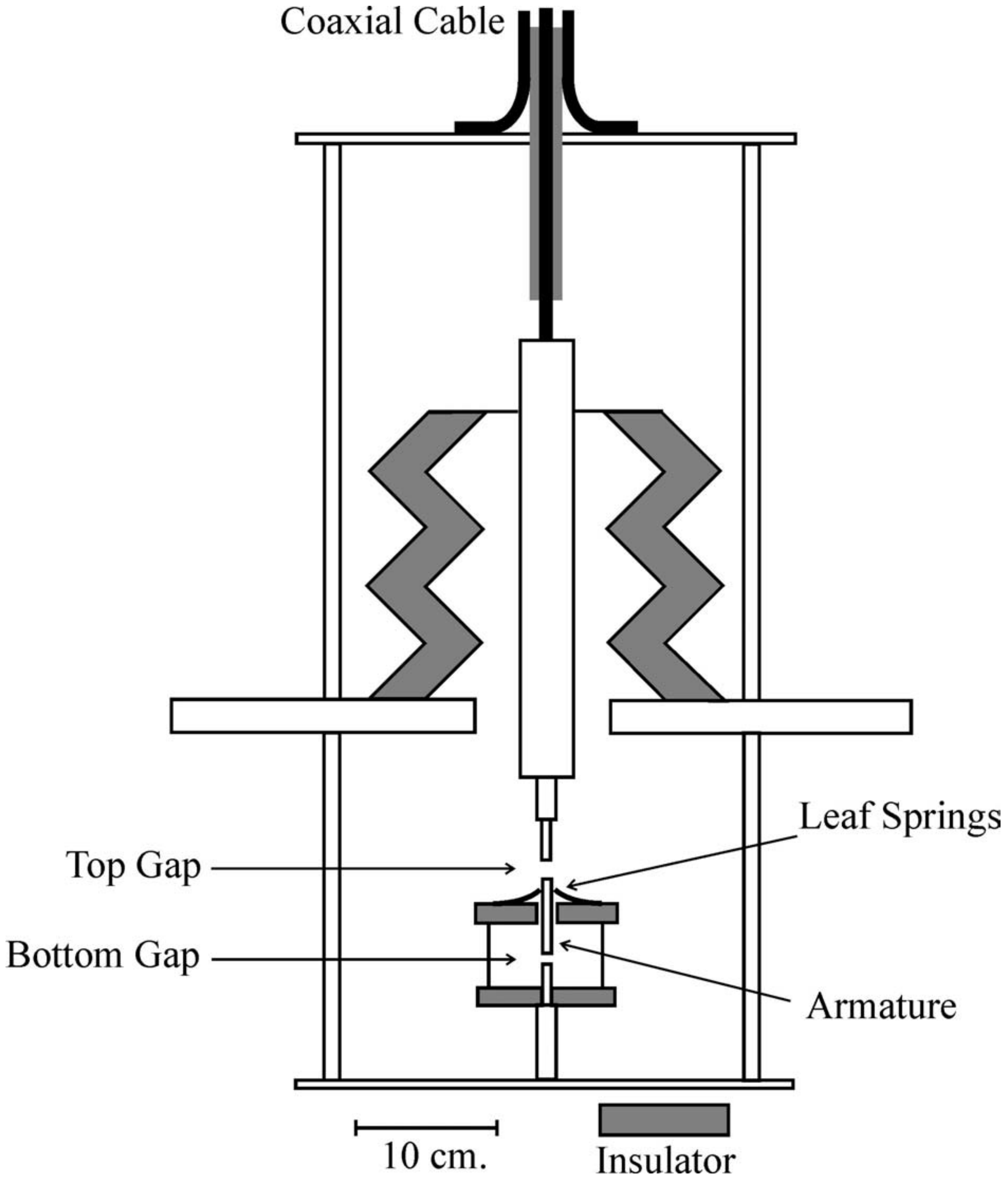

Figure 1 : Schematic of GPR Experiment [2]

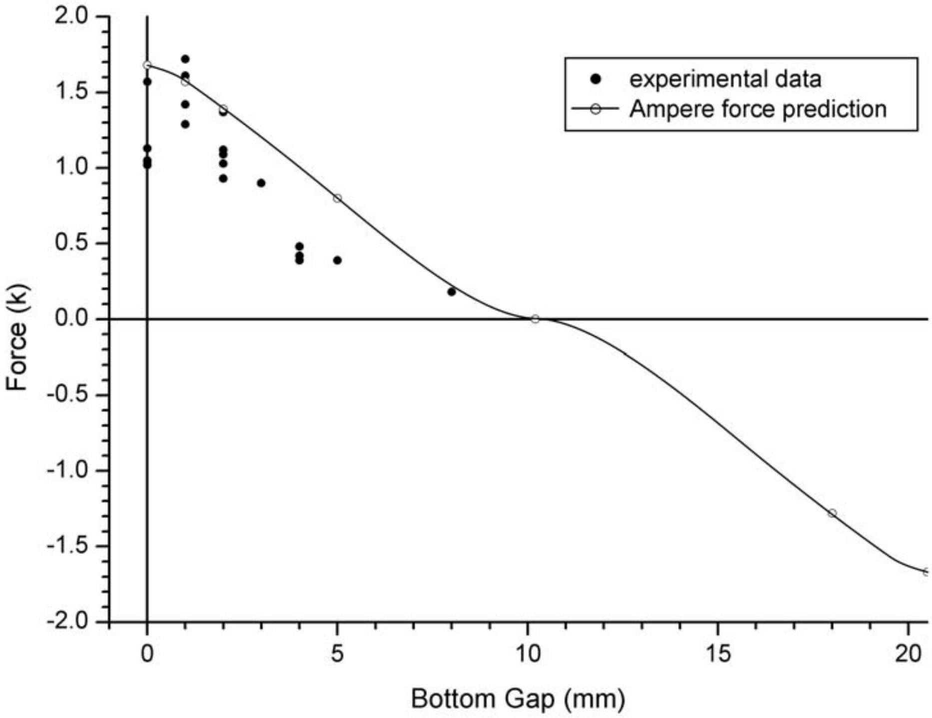

Figure 2 : Data from GPR experiment [2] including theoretical Ampère prediction

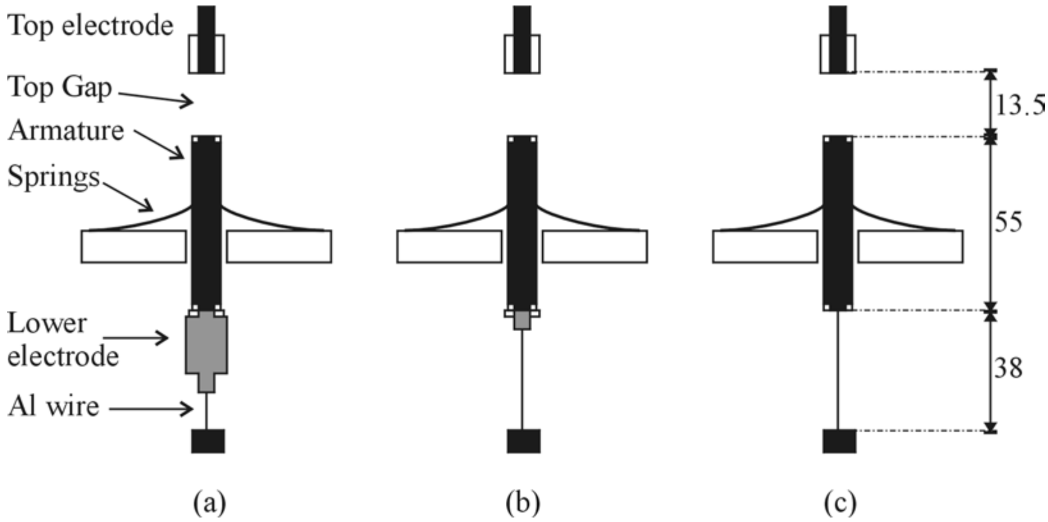

Figure 3: Schematic of the electrodes in the type (a), (b) and (c) configurations

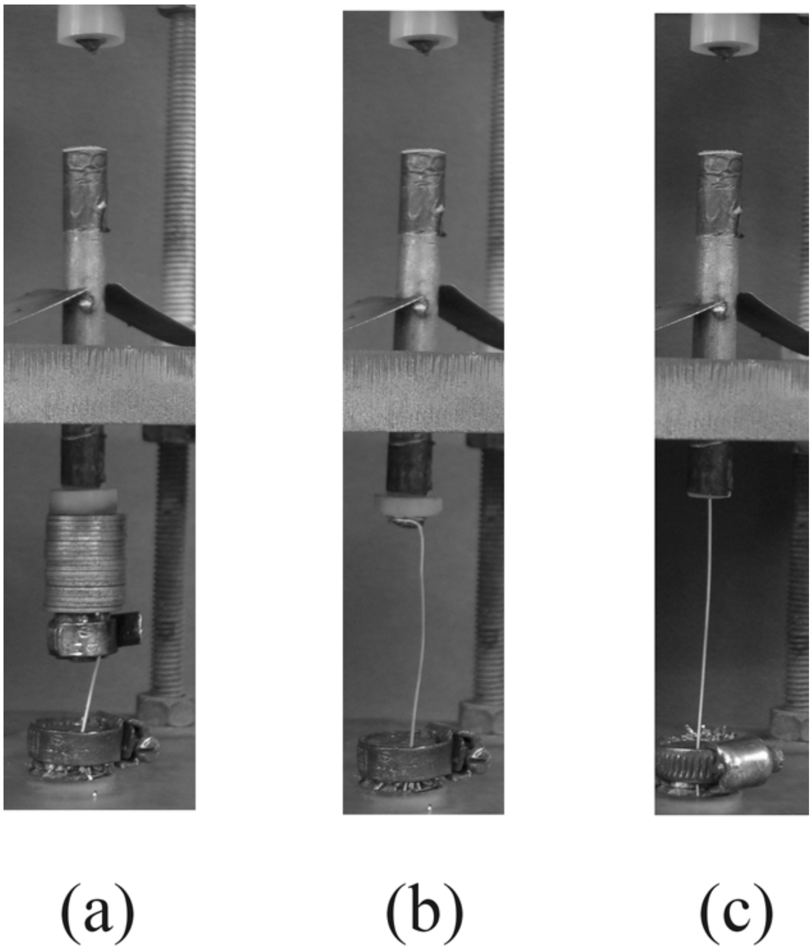

Figure 4 : Photos of the electrodes in the type (a), (b) and (c) configurations

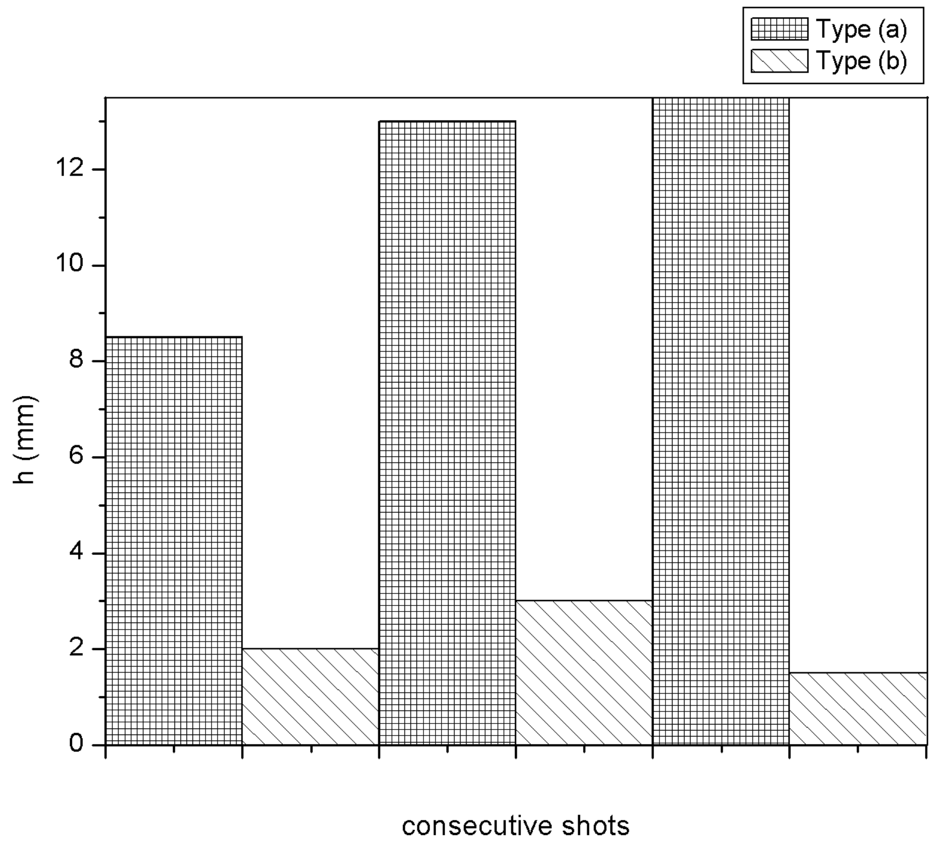

Figure 5 : armature height gain measurement for alternating type (a) and (b) shots

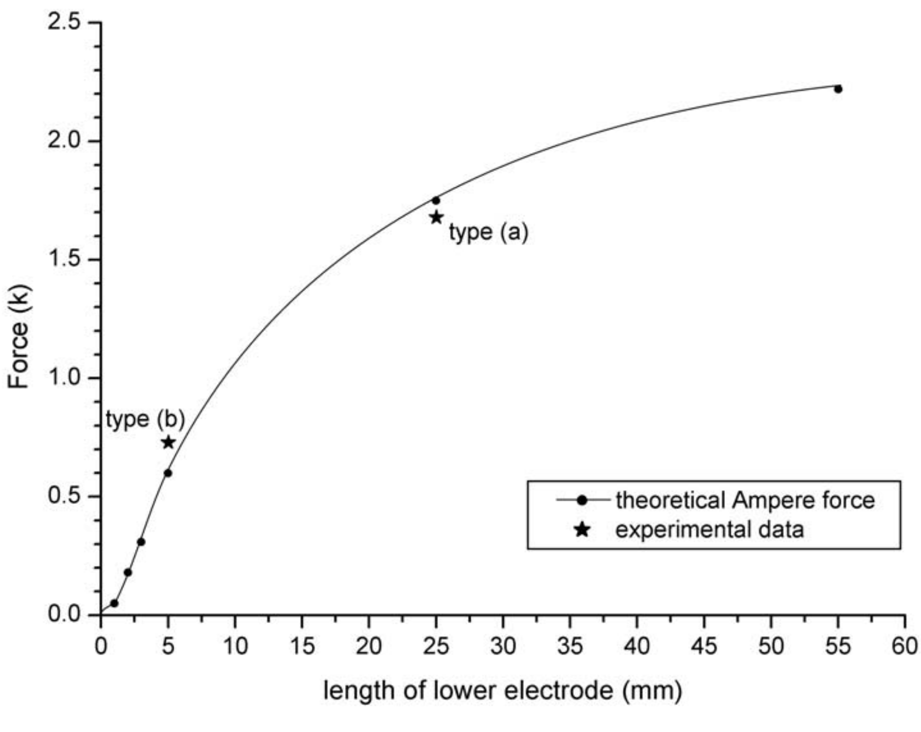

Figure 6 : Ampere force calculation and experimentally measured repulsion force between the lower electrode and the armature

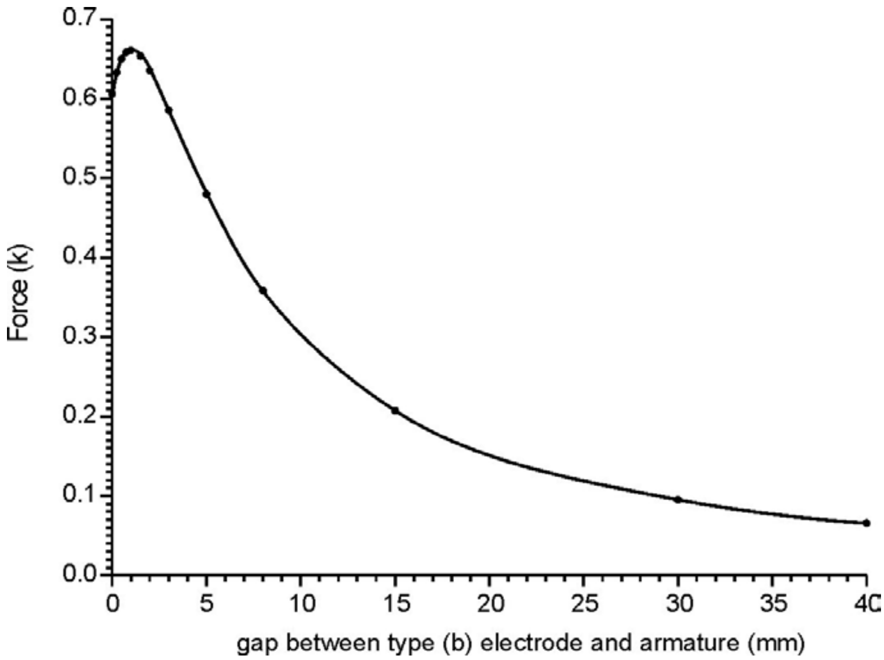

Figure 7 : Theoretical Ampère repulsion force constant (k) between the type (b) electrode
and the armature with a varying gap between them