ABSTRACT

Lenz’ Law is often demonstrated in classrooms by the use of Elihu Thomson’s jumping ring. However, it is ironic that a thorough analysis of the physics of the AC jumping ring reveals that the operation is due mainly to a phase difference, not Lenz’ Law. A complete analysis of the physics behind the AC jumping ring is difficult for the introductory student. We present a design for a pulsed jumping ring which can be fully described by the application of Lenz’ Law. Other advantages of this system are that it lends itself to a rigorous analysis of the force balances and energy flow. The simple jumping ring apparatus closely resembles Thomson’s, but is powered by a capacitor bank. The jump heights were measured for several rings as a function of energy stored in the capacitors. A simple model describes the data well. Currents in both the drive coil and ring are measured and that of the drive coil modeled to illuminate some properties of the capacitors. An analysis of the energy flow in the system explains the higher jump heights, to 2 meters, when the ring is cooled.
INTRODUCTION

Many students have witnessed a professor launch a metallic ring off of a coil and into the air. This so-called Thomson jumping ring has long been a staple, in-class demonstration of Lenz’ Law for introductory electricity and magnetism students\(^1\). Richard Feynman proposed the common explanation of the phenomenon by likening the repulsion of the ring by the coil to that resulting from the juxtaposition of two like magnetic poles\(^2\). Although an interpretation similar to Feynman’s is commonly proffered to students, a much more sophisticated and accurate interpretation is found in the literature. Quinton\(^3\), Churchill and Noble\(^1\), Mak and Young\(^4\), and Hall\(^5\), all show that the repulsion of the ring is due mainly to the phase difference between the magnetic fields of the coil and the ring. Schneider and Ertel further refine the analysis by including the function of the iron core in the jumping ring apparatus\(^6\). The complex analysis results from using alternating current (AC) to power the ring, often at low frequencies (60 Hz) where inductance does not dominate circuit response. The jumping ring apparatus we describe here is powered by a high DC bias (up to 2000 V) stored on capacitors. The large voltage induces large currents on a very short time scale. Inductance then dominates, and the dominant physics is the application of Lenz' Law. A pick-up coil is used to unveil other features of interest that are enabled by this driving mechanism. The magnetic fields of the driving coil and the ring can be measured, and, through a calculated or measured mutual inductance, the time-dependent currents can be found. They are used to determine the fate of the energy stored in the capacitor bank and the time-dependent motion of the ring.

CONSTRUCTION OF THE JUMPING RING APPARATUS
The jumping ring apparatus consists of three main assemblies, the driving solenoid (coil), the capacitor bank, and the high voltage isolation switch. These three elements are housed inside an insulating, wood-framed, plexiglass enclosure. The enclosure provides needed isolation for the high-voltage circuitry as well as a protective barrier from possible capacitor breakdown. Plexiglass was chosen as it makes the inner-workings of the device readily visible.

The driving coil (Fig. 1(a)) is built around PVC pipe (Fig. 1(b)), with a diameter of 5 cm (2"). This pipe houses the core (Fig. 1(c)) of the solenoid and isolates the wire from the core. The pipe provides mechanical stability, but plays no electrical role. The core of the solenoid was packed with iron rods to increase the permeability of the space within the coil. Two hundred iron rods, 61 cm (24") long and 1.6 mm (1/16") in diameter, rest axially inside the pipe. These rods were enameled to prevent eddy currents within the core. Although the core extends 61 cm, the winding about the coil is only 22 cm (8.75") long. The winding is subject to a large voltage during operation so it must remain within the plexiglass enclosure. Twenty-gauge, high-temperature, bus wire was utilized for the winding. Two 91 m (300 ft) spools were soldered together and wound ~1250 times for a total of five layers thickness around the core. Between each layer, a precautionary layer of electrical tape was applied to guard against any possible flaw in the insulation of the wire. For a 2000 V driving potential, the potential difference between adjacent layers of the winding could reach 800 V at one end. The extra insulation guarded against the possibility of electrical arcing at these points.

The capacitor bank was composed of two main elements, capacitors (Fig. 2(a)), and a high voltage power supply (Fig. 2(b)). These two elements were assembled in series with a current limiting resistor (Fig. 2(c)). A 2000 V, 10 mA photomultiplier tube power supply was implemented in this design, although many other options, such as voltage-multipliers, would
have been viable. The power supply charged the capacitors with a voltage between 600 and 2000 V across the current limiting resistor and capacitors. The 604 kΩ current limiting resistor was assembled from thirteen 47 kΩ resistors. It limited the charging current to 1-3.3 mA. The large number of series resistors was needed so that the voltage rating of each resistor was not exceeded. One-half watt resistors provide sufficient power handling capabilities. Three 4 µF, 2500 V (Newark Electronics) capacitors were wired in parallel (see Fig. 2(a)) to provide a measured capacitance of 12.7 µF. This effective capacitance in series (see Fig. 2(c)) with the current limiting resistor produced an RC circuit with a time-constant of 7.25 seconds.

The capacitor bank and solenoid should remain electrically isolated until the operation of the jumping ring. Therefore, the connection of the capacitor bank and solenoid circuits had to be accomplished by a remote method since the voltage and current (up to 2000 V and several amps) could prove lethal if improperly handled. The design presented here utilized a solenoid-driven high voltage switch (Fig. 2(d)) that was surplus from a plasma physics experiment, although high voltage solid state switching elements such as a field effect transistor or a silicon controlled rectifier would suit as substitutes. The switch consisted of a solenoid and plunger. The solenoid was activated by, 120 VAC, 60 Hz wall current controlled with a simple light switch.

Two types of rings were used. Each type was tested at both room temperature and shortly after being cooled in liquid nitrogen. The copper ring was a gasket from a conflat-type ultra-high vacuum flange. The inner and outer radii were 3.18 and 4.44 cm, respectively, and the thickness 0.159 cm. The mass was 0.0389 kg. The aluminum ring was made with the same dimensions, resulting in a mass of 0.00752 kg. The ring was rested on the plexiglass cover, and had to jump over 30.5 cm (12") before clearing the top of the PVC pipe and core.
JUMP HEIGHTS

Jump heights were measured for a range of energies stored on the capacitors, for each ring described above. All measurements were made after allowing the apparatus to charge for 2 minutes. A wall-mounted ruler was utilized for the height measurements. Although a video-based technique could provide more accuracy, we found that averaging 10 trials resulted in a few percent (2-10%) error in all but the smallest jump heights. The results are shown in Figure 3. The apparatus is able to launch a ring nearly 2 m above its starting point. There is a large disparity between the room temperature and cryogenic jump heights, as has been observed with AC jumping ring apparatus. The voltage dependence of the jump height is nonlinear, in contrast to the linear behavior observed by Sumner and Thakkar\(^7\) for an AC jumping ring apparatus, for reasons described below. Our data follows a parabolic minus linear dependence.

We model the jump height with Newton's laws, obtaining the equation

\[
\frac{dv}{dt} = \frac{1}{\tau} \sqrt{C \zeta/m} \ V \ e^{-t/\tau} \ - \ g \ - \ kv,
\]

where the last term is velocity-dependent air resistance, the middle term is the gravitational acceleration, and the first term derives from the magnetic driving force. The currents are expected to decay exponentially, with time constant \(\tau\) that is much less than the flight time of the ring. The coefficient results from assumption that the force integrated over all time supplies an impulse sufficient to convert a fraction \(\zeta\) of the energy on a capacitor \(C\) at voltage \(V\) into kinetic energy of the ring with mass \(m\) (intial velocity = \(\int F/m \ dt = \sqrt{C \zeta/m} \ V\) with \(F = F_0 e^{-t/\tau}\)). The rest of the energy on the capacitor is lost to resistance in the coils, radiation, etc. Eqn. (1) can be integrated to give
\[ v(t) = \left[ \frac{g}{k} + \frac{1}{\tau} \sqrt{C\zeta/m} \frac{V}{1/\tau-k} \right] e^{-kt} - \frac{1}{\tau} \sqrt{C\zeta/m} \frac{V}{1/\tau-k} e^{-t/\tau} - \frac{g}{k}, \]

where we have chosen \( v = 0 \) at \( t = 0 \). This differs from previous treatments for AC jumping rings, that assumed a nonzero initial velocity. They required such an assumption since the constant upward force nearly compensates the gravitational force, leaving the viscous force of the air as dominant (resulting in behavior linear in \( V \)). In our case, we must explain the fact that we saw no jumping of the ring at all for voltages \( \sim 700 \) V and below. This results from the magnetic force being insufficient to overcome the weight of the ring, and falls naturally from our model. Another integration of the velocity equation gives the height \( z(t) \):

\[ z(t) = \frac{1}{k} \left[ \frac{g}{k} + \frac{1}{\tau} \sqrt{C\zeta/m} \frac{V}{1/\tau-k} \right] (1-e^{-kt}) - \sqrt{C\zeta/m} \frac{V}{1/\tau-k} (1-e^{-t/\tau}) - \frac{gt}{k}. \]

The jump height \( h \) will be \( z(t_{\text{top}}) \), when the ring reaches its maximal height, i.e. when the velocity is zero. We evaluate Eqn. (2) at \( v=0 \) to obtain \( t_{\text{top}} \), using the fact that \( t_{\text{top}} \gg \tau \), so \( e^{-t_{\text{top}}/\tau} \approx 0 \):

\[ t_{\text{top}} = \frac{1}{k} \ln \left[ 1 + \sqrt{C\zeta/m} \frac{kV}{g\tau(1/\tau-k)} \right] \approx \sqrt{C\zeta/m} \frac{V}{g\tau(1/\tau-k)} - \sqrt{C\zeta/m} \frac{kC\zeta V^2}{2g^2 m\tau^2 (1/\tau-k)^2}, \]

where the last equality requires that the second term in the logarithm be much less than one. We now substitute into \( z \) to obtain

\[ h = \frac{C\zeta}{2mg\tau(1/\tau-k)} V^2 - \frac{1}{1/\tau-k} \sqrt{C\zeta/m} V \approx \frac{C\zeta}{2mg} V^2 - \tau \sqrt{C\zeta/m} V. \]

The equation is of the form \( h = A V^2 - B V \). Fits to this function are shown in Figure 3. The fit parameters are found in Table 1. The last equality is valid when the air resistance is small, in particular when \( k\tau \ll 1 \). Multiplying both sides by \( mg \), we see that the potential energy of the ring is the fraction \( \zeta \) of the energy on the capacitor, less a term proportional to \( V -- \) emanating from the lift-off condition. The numerical value of \( \zeta \) is found from the fit parameter \( A \), and the
voltage below which the ring will not jump from the ratio of the fit parameters. Both are found in Table 1. It is interesting to find the small fraction of the energy in the capacitor bank that is transferred to kinetic energy of the ring. Below, we quantitatively determine the energy lost to ohmic heating in both the primary and secondary circuits. The remaining energy dissipates in the capacitors or radiates away. Note that the energy fractions are larger and minimum jump voltages lower for the cooled rings. This is due to the higher conductivity, hence lower energy loss, for currents in the rings at low temperature.

**CURRENTS IN THE COIL AND RING**

A 2-turn pick-up coil was mounted < 1 cm below the starting position of the ring. It is used to monitor the current in the ring and solenoid. The mutual inductance \( M \) is required to quantify the currents. We can estimate \( M \) for two loops of radius \( a \) (0.03 m here) spaced along their axes by a distance \( R \) (0.005 m here) from the following formula:

\[
M = 4\pi \mu \pi a^2 \int e^{Rx} J_1(ax) \, dx.
\]

The integration is performed numerically. A value of the permeability \( \mu \) of 6\( \mu_0 \) was used since the measured self-inductance of the solenoid was a factor of 6 larger than that calculated for an air-core inductor. The result is \( M = 4.6 \times 10^{-7} \) H, in good agreement with the measured value of 4.77\( \times 10^{-7} \) H. A lock-in amplifier measured the voltage induced on a split ring and on a current monitoring resistor in series with the (driven) pick-up coil. The relation \( M = V/(dI/dt) = V/(\omega I) \) gives \( M \). \( M \) was measured for several distances as the ring was moved up the core. An exponential decrease was found along the entire 12" length of the core: \( M = 4.8 \times 10^{-7} e^{-z/0.09 \, m} \) H. A simple estimate of \( M \) between the apparatus' driving solenoid and the pick-up coil follows from integrating the above \( M \) multiplied by the solenoid turns/length and divided by 2 (above is...
for a 2-turn pick-up) from z=0 to 0.22, the coil length. The $1.1 \times 10^{-4}$ H value is close to the measured $1.22 \times 10^{-4}$ H.

A Fluke Scopemeter captured the pick-up coil voltage without a ring in place, and during the jump of a room temperature Al ring, both with the capacitors charged to 1800 V. The former is used to find the driving coil current $I_{\text{coil}}$. The difference between the latter and former is used to measure the ring current $I_{\text{ring}}$, with the assumption that the field from the ring does not influence the current in the driving coil. The assumption is accurate for our rings due to the large ratio of inductance. We have found the measurements of currents to be extremely reproducible for different jumps, with the main differences being slight time shifts between the $I_{\text{coil}}, I_{\text{ring}}$ pairs from different trials, probably due to triggering accuracy. The measured voltage on the pick-up coil is proportional to the rate of change of the magnetic field, hence current in the coil or ring. Mathematically, $I = \int M^{-1} V_{\text{pick-up}} \, dt$. The measured mutual inductances are used, and the voltage data numerically integrated. The results are shown in Figure 4. Under these conditions, the ring jumps to the top of the core, 0.3 m. The current, hence field, of the ring is very close to 180° out of phase with that of the driving coil, hence the simplistic Lenz' Law explanation of the jump is correct. One might have expected that there would be just one pulse of magnetic field, but the system is actually underdamped, and we see LC oscillations. The condition for critical damping relates the damping coefficient to the resonant frequency, yielding $R = 2 \sqrt{L/C}$. A resistance of ~360 Ω rather than 6.9 Ω is needed. We added an additional 360 Ω as 22 of 15 Ω, 1/2 W resistors to avoid power and voltage limitations of the resistors. The current traces are shown in Figure 5, and nicely illustrate a Lenz' Law type of behavior. Unfortunately, the additional energy loss in the resistors reduces the current magnitudes, see the figures, and the aluminum
ring jumps just a few mm rather than 0.3 m.

The current in the driving coil can be modeled as a RLC circuit, with initial condition that the voltage on the capacitor is $V_{C0}$. The solution of the differential equation is

$$I_{coil} = I_0 e^{-\alpha t} \sin \omega t; \quad \omega = \sqrt{1/LC - R^2/4L^2}; \quad \alpha = R/2L; \quad I_0 = V_{C0}/\omega L,$$

(6)

where $\alpha$ and $\omega$ are found by requiring that the $\sin \omega t$ and $\cos \omega t$ terms separately vanish, and $I_0$ from integrating $C \, dV_C = I \, dt$ over all time and applying the initial condition. The result is plotted in Figure 4, and agrees remarkably well, considering the few free parameters (measured values are used to calculate all parameters except the decay time constant, which was reduced by a factor of 6 from the calculated value). The behavior at short times exhibits an approximate frequency doubling and amplitude halving. Since the frequency changes, a nonlinear process is involved. We believe that the behavior derives from the temporal response of and hysteresis in the capacitor. At small times, the dielectric polarization does not respond completely, so the capacitance is effectively a factor of two reduced, as is observed. When the capacitor recovers, it rejoins the theoretical curve.

**ENERGY ANALYSIS**

If all the energy stored in the capacitors was converted to potential energy of the ring, then $1/2 \, CV^2 = mgh$, and our Cu ring, of mass $m$, would reach a height of $h = \sim57$ m when the capacitor, $C$, was charged to $V = 2000$ V. The assumption of perfect energy conversion is, of course, unrealistic, yet it is easily understood by introductory students and serves as reminder that a proper energy analysis is required. The pulsed jumping ring allows this type of analysis.

Energy from the capacitors is lost to ohmic heating in the drive coil, $E_{coil}$, to ohmic heating in the ring, $E_{ring}$, through air resistance, to dissipation in the capacitors and by radiation.
The remainder, a small fraction, is converted to potential energy of the ring, $U_{\text{ring}}$. Since we have measured the currents in the ring and drive coil, we can estimate the ohmic energy losses. The current at each time measured is squared and multiplied by the resistance of the drive coil (6.9 $\Omega$ or 366 $\Omega$ with critical damping) or that of the aluminum ring (330 $\mu\Omega$). This is then numerically integrated. The $E_{\text{lost}}$ column of Table 1 includes the energy lost via air resistance, that lost in the capacitors, and the energy lost from the primary circuit, but not coupled into the ring due to the rapid decrease of $M$ with height, as described above. For the jumps with current shown in Figure 4 and Figure 5, respectively, the energy sums $E_{\text{coil}} + E_{\text{ring}} + U_{\text{ring}} = E_{\text{total}}$ are $1.6 \, \text{J} + 6.3 \, \text{J} + 0.04 \, \text{J} = 7.9 \, \text{J}$ and $12.1 \, \text{J} + 0.2 \, \text{J} + 0.0004 \, \text{J} = 12.3 \, \text{J}$. The air resistance contribution in both cases is negligible. Both sums total less than the 20.6 Joules of energy stored on the capacitors, $E_{\text{cap}}$. Other trials with critical damping totaled closer to or slightly higher than the 20.6 J, indicating that the error is rather large in the critical damped measurements. Most of the trials without critical damping, as in Figure 4, yielded similar total energies -- much less than the 20.6 J. We do not know why these measurements were more reproducible than those with critical damping. Perhaps the resistors in the critical damping circuit were damaged by the high currents. The lower $E_{\text{total}}$ is probably due to the significant height to which the ring jumps, and therefore the reduced efficiency of energy coupling. The coupling relates to the $\zeta$ parameter in Eqns. 1-5, which is $U_{\text{ring}}/E_{\text{cap}}$. The reduced coupling to the ring follows from the measured exponential decay of $M$ with $z(t)$, which is given in Eqn. 3 and measured below. The small coupling $\zeta$ could be improved by altering the shape of the ring, as has been analyzed before.$^8, 6, 9$ We note here that changing the ring can effect the validity of the Lenz' Law description of the jump and the assumptions used in obtaining the currents.
What we learn from this exercise is that most of the energy for the critical damping case is dumped into the extra resistors, whereas a large fraction in the standard case is lost in the ring. For higher jumping heights, the energy lost in the ring should decrease. This is why the cold ring jumps so much higher. Since the voltage induced around the ring would be the same, the current flow would increase by the ratio of ring resistance $R_{RT}/R_{cold} = 3 \, \mu \Omega \cdot \text{cm}/0.2 \, \mu \Omega \cdot \text{cm}$ for Al or $1.1 \, \mu \Omega \cdot \text{cm}/0.07 \, \mu \Omega \cdot \text{cm}$ for Cu. The energy loss $E_{ring}$ depends on the current squared times the resistance, so should increase as $R_{RT}/R_{cold}$. A quick look at the above numbers precludes such an increase in energy loss, as it would bring the total above that stored on the capacitors, so apparently the field from the ring becomes large enough to alter the flow of current in the drive coil, invalidating one of our assumptions. This could be included in the extraction of the currents from the measured pick-up coil data, but introduces extra complication and parameters that we avoid with the room temperature rings analyzed. Of practical interest is that cooling the drive coil should not produce nearly as dramatic effects as cooling the ring.

**MOTION OF THE RING**

Newton's laws determine the motion of the ring. The force of gravity and the force on the current-carrying loop due to the current in the solenoid generate an acceleration. We assumed in the jump-height analysis section above that the magnetic force acts for only a short period of time, following which the ring undergoes vertical projectile motion, free fall. We will find experimentally that this is true. The magnetic force is proportional to the product of the current in the driving solenoid and the current in the ring. Since we have measured both, we can experimentally determine the magnetic force, then integrate the acceleration to obtain the time-dependent position. We need the geometric-dependent proportionality constant to quantitatively
find the force. We calculate the proportionality constant for \( N \) rings of radius \( a \) and current \( I_1 \) pushing one ring of diameter \( a \) that is a distance \( d \) along the same axis, with current \( I_2 \). \( N \) is the effective number of turns that contribute to the force. We use \( N = 511 \) as was found in the estimation of \( M \) between the drive and pick-up coils (also related to magnetic field coupling). Note that this implies that a shorter coil with more layers would be more effective than the current design. The magnetic force is given by a standard relation\(^{10}\):

\[
F_z = -\frac{\mu_0}{4\pi} I_1 I_2 N \int \int \frac{\mathbf{r} \times \mathbf{d}l_1 \cdot \mathbf{d}l_2}{r^2} = -\frac{\mu_0 d}{4\pi a} I_1 I_2 N \int \int \frac{2\pi 2\pi \cos(\theta_1 - \theta_2)}{(2-2\cos(\theta_1 - \theta_2) + (d/a)^2)^{3/2}} \, d\theta_1 d\theta_2. \tag{7}
\]

The \( d\l \)'s are line elements along the loops, and \( \mathbf{r} \) the vector from the loop 1 element to the loop 2 element. The \( z \)-component of the force gives lift, and is the only component that does not cancel during the integration. The integral in Eqn. 7 is evaluated numerically for \( d/a = 0.8 \), corresponding to the ring \( \sim 2 \) cm above the top of the driving coil. This gives \( a_z = -0.07 I_{\text{coil}} I_{\text{ring}} - 9.8 \) in SI units. This is shown in Fig. 6 for the currents shown in Fig. 4. Numerical integrations are used to find the velocity, and from that the vertical position as functions of time.

The data show that the velocity reaches close to its maximum value within the first 25 msec of flight (and first 0.02 m of the jump). This is much less than the total flight time, and the initial velocity \( v_0 = 2.7 \) m/s indicates, with energy conservation \( m v_0^2/2 = mgh \), that a maximum height \( h = 0.37 \) m should be attained. This is in reasonable agreement with the actual 0.31 m jump height. Using the same expression (including the same proportionality constant) for the acceleration as above, but with the critical-damped currents of Fig. 5, we find that the initial velocity, 0.1 m/s, is attained in \( \sim 3 \) msec and by 0.2 mm height. The predicted jump height is 1 mm, also in reasonable agreement with the estimated few mm jump (the top of the jump is reached in about 14 msec, so accurate measurement is difficult).
As expected for a pulsed jumping ring, kinetic energy is injected into the ring by a series of pulses, appearing as step-like jumps of the velocity. Vertical projectile motion ensues, most of which is not shown in the figure.

**SUMMARY**

A pulsed jumping ring apparatus is described. It is capable of launching rings as high as most AC jumping ring devices. The behavior, however, can be accurately described as resulting from Lenz' Law. Other attributes allow a proper analysis of energy flow in the apparatus, which offers insights into the performance gains due to cooling of the rings. The pulse can be used to trigger a digital oscilloscope for acquisition of the current flowing in the driving coil and ring via their coupling to a pick-up coil. Besides providing a graphic illustration of the relative phases of the current, they can be used to calculate energy dissipation. Most of the parts can be inexpensively obtained or built, and others are often found unused in department labs. We therefore suggest the apparatus as a suitable demonstration apparatus for introductory students or a more involved laboratory tool for more advanced students. The apparatus described here, built by advanced undergraduates, is mobile (the weight of the solenoid switch within the unit being the primary impediment), and has been used several times as a classroom demonstration for introductory students.
REFERENCES

FIGURE and TABLE CAPTIONS

Figure 1. A picture of the pulsed jumping ring apparatus. Several parts are labeled for identification: (a) the iron core, (b) the PVC pipe, (c) the driving coil, (d) the capacitor bank, (e) the high voltage power supply, and (f) the high-voltage solenoid switch. The solenoid actuating switch is on the wood in back.

Figure 2. A schematic diagram of the drive circuit. The capacitors (a) are charged by a high voltage supply (b) through current limiting resistors (c). A high voltage switch (d) closes to dump the energy to the driving coil (e).

Figure 3. Measured jump heights as a function of voltage on the capacitor bank are shown for the four ring types. The error bars for the lower two plots are smaller than the symbol size. Also shown are quadratic minus linear fits to each dataset, and, for comparison, the best-fit pure quadratic function for the case of a cooled aluminum ring.

Figure 4. The measured currents obtained from integrating the voltage on the pickup coil and converting to amps with the independently measured mutual inductance. An aluminum ring was used, and the capacitors charged to 1800 V. Current in both the driving coil and ring are shown on different scales. A model fit to the coil current illustrates its underdamped behavior.

Figure 5. The measured currents obtained from integrating the voltage on the pickup coil and
converting to amps with the independently measured mutual inductance. An aluminum ring was used, and the capacitors charged to 1800 V. Current in both the driving coil and ring are shown on different scales. Extra resistance was added between the capacitors and the driving coil to critically damp the RLC circuit.

Figure 6. The measured currents from Fig. 4 supply the inputs for calculation of the magnetic force as a function of time. This gives the acceleration, and through numerical integrations, the time-dependent velocity and position shown here.

Table 1. The fit parameters and chi-squares are shown for the plots of Fig. 4. Also shown is the theoretical voltage above which the ring should jump, since the electromagnetic force exceeds the gravitational force on the ring, the fraction of energy, $\xi$, of the capacitors that is available to drive the ring and the decay time of the driving force, $\tau$, as deduced from the fit. The other two columns provide the energy in joules that is available to drive the ring, and the energy lost, that is, the difference between the available energy and the maximum potential energy that the ring attains.
<table>
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<th>Fit function</th>
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<th>ζ</th>
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<th>τ</th>
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Table 1, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz' Law" for *American Journal of Physics*. 
Figure 1, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz’ Law" for *American Journal of Physics*. 
Figure 2, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz’ Law" for American Journal of Physics.
Figure 3, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz’ Law" for American Journal of Physics.
Figure 4, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz’ Law" for *American Journal of Physics.*
Figure 5, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz’ Law" for
Figure 6, Tanner et al, "A pulsed jumping ring apparatus for demonstration of Lenz’ Law" for American Journal of Physics.