

The jumping ring experiment

M Baylie, P J Ford, G P Mathlin and C Palmer¹

Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK

E-mail: g.mathlin@bath.ac.uk

Abstract

The jumping ring experiment has become central to liquid nitrogen shows given as part of the outreach and open day activities carried out within the University of Bath. The basic principles of the experiment are described as well as the effect of changing the geometry of the rings and their metallurgical state. In general, aluminium rings are used, but the effect of using copper rings is briefly discussed.

Introduction

The jumping ring experiment is a striking demonstration of Faraday's laws of electromagnetic induction and also of Lenz's law. The basic experimental set up is illustrated in figure 1, and a schematic of the actual jumping ring apparatus is shown in figure 2. An aluminium ring is placed above the coil, which is connected to the mains electricity supply. On quickly switching the supply on and off, a pulse of electricity is sent to the coil and the aluminium ring normally jumps to a height of between 20 and 30 cm. The effect is particularly striking if the ring is then cooled down to the temperature of liquid nitrogen, when a jump of some 2–3 m can be observed. This is because the much lower electrical resistance of the ring (reduced by about an order of magnitude from its resistance at room temperature) means that the induced current is much greater and so is the force of repulsion. Further details of the experimental set up are given by Ford and Sullivan [1].

The jumping ring experiment is an important feature of lectures/demonstrations given mainly to school students who respond most enthusiastically when a very large jump height is observed. It was during one of these lectures by Peter Ford (PJF) that a curious incident occurred. The cooled

ring jumped up nearly three metres as normal; it then landed on its edge and rolled several metres before finally disappearing down a hole in the floor at the back of the stage where the lecture was being given. Initial attempts to recover it proved unsuccessful. However, this was thought not to be a problem. With uncharacteristic foresight PJF had measured the dimensions of the ring and its mass.

The Physics Department workshop technician quickly made up two more rings. However, to our surprise, the new rings when cooled only jumped to approximately half the height of the original ring. A further source of aluminium sheet from the main university workshop produced rings which jumped to a similar height as those made up in the Physics Department workshop. Through the good offices of the university cleaning staff, the original ring was recovered from under the stage, and it was quickly shown that the height jumped when cooled down had been unaffected by the few weeks spent underneath the stage. The original ring had been produced in 1991, when it formed part of a student project to mark the 200th anniversary of the birth of Michael Faraday. The question then arose as to what was different in the aluminium rings in the intervening 15 years? This led to another student project re-examining various aspects of the jumping ring experiment, which over the years has been the subject of several investigations [2–9].

¹ Present address: Physics Department, Imperial College London, South Kensington Campus, London SW7 2AZ, UK.

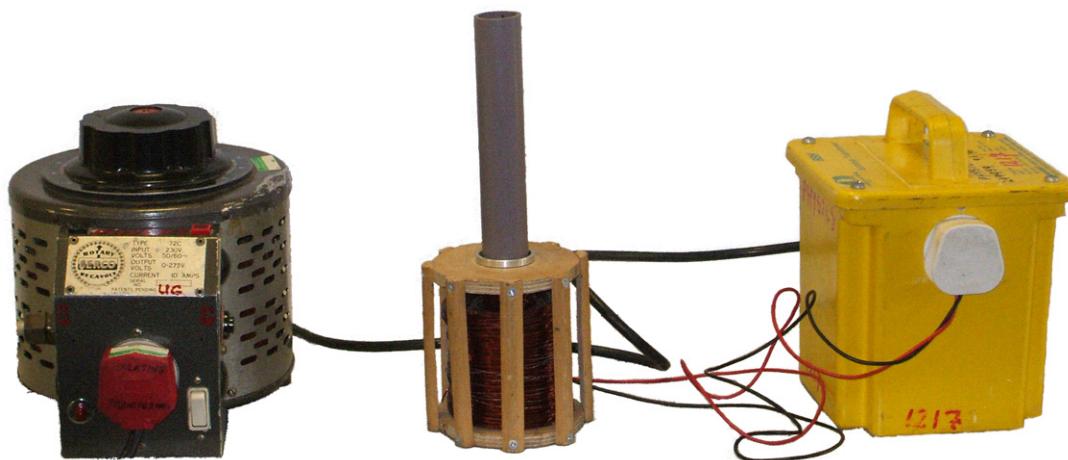


Figure 1. The jumping ring equipment. From left to right: variable mains transformer, jumping ring apparatus and safety isolating transformer.

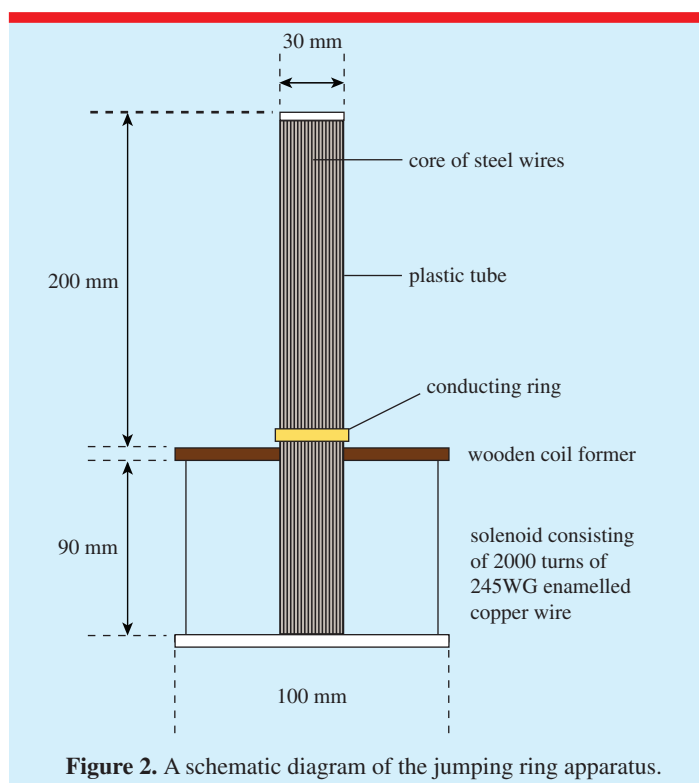


Figure 2. A schematic diagram of the jumping ring apparatus.

The person credited with the invention of the jumping ring experiment is Elihu Thomson, and it is sometimes referred to as the ‘Thomson ring’ experiment. He had an interesting life. He was born in Manchester in 1853, but the family emigrated from England to America five years

later. In 1879 he founded the Thomson–Houston Electric Company, which merged with the Edison Electric Company in 1882 to form the General Electric Company. He was a prolific inventor, and in a long career spanning over five decades was granted nearly 700 patents. The jumping

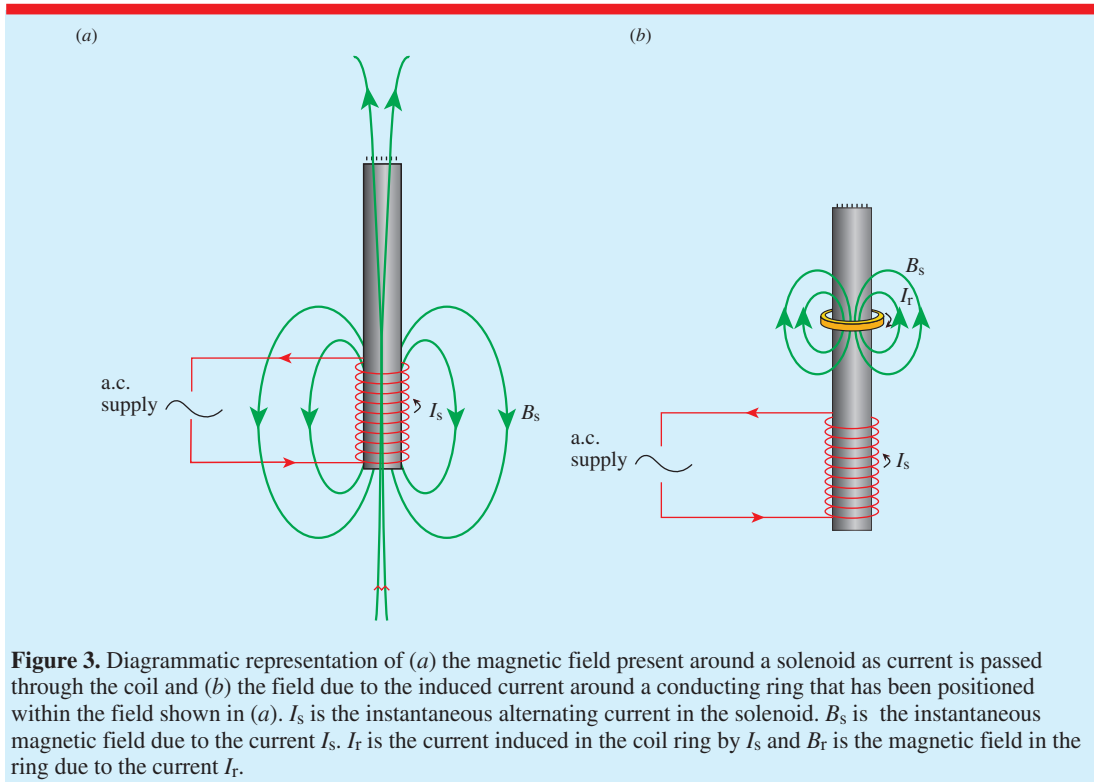


Figure 3. Diagrammatic representation of (a) the magnetic field present around a solenoid as current is passed through the coil and (b) the field due to the induced current around a conducting ring that has been positioned within the field shown in (a). I_s is the instantaneous alternating current in the solenoid. B_s is the instantaneous magnetic field due to the current I_s . I_r is the current induced in the coil ring by I_s and B_r is the magnetic field in the ring due to the current I_r .

ring experiment was first demonstrated in 1887 at a meeting of the American Institute of Electrical Engineers. It has been shown many times since, a notable example being that of Lord Rayleigh in 1891, at the Royal Institution in London, during a lecture to mark the centenary of the birth of Michael Faraday [1].

Theory

A current at a fixed frequency (50 Hz in the United Kingdom) is applied to the solenoid as shown in figure 3. This causes a magnetic field, B_s , to be induced. The strength of B_s depends upon the current, I_s , applied and the number of turns in the coil. B_s induces the current I_r in the ring. The electromotive force (emf) associated with this current is described by Faraday's law of electromagnetic induction:

$$\varepsilon = -\frac{d\Phi}{dt},$$

which states that the magnitude of the induced emf is proportional to the time rate of the change of magnetic flux. The minus sign embraces Lenz's

law, which states that '... the induced emf [and induced current] are in such a direction as to oppose ... the change that produces them' [10]. This is of course necessary since, if the direction of motion was not opposed, conservation of energy would be violated. The induced current itself creates the magnetic field in the ring, B_r , and, because the sense of the ring current is opposite to that of the solenoid current, the two magnetic fields repel each other, giving rise to the jump effect. The magnitude of the force between the ring and the solenoid depends upon the strength of the magnetic field B_s , the ring current, and the dimensions of the ring.

By lowering the temperature of the ring, we lower its electrical resistance and hence increase the induced ring current. This, in turn, increases the strength of the magnetic field B_r , thereby causing the ring to jump higher. Using liquid nitrogen (boiling point 77 K) as the coolant means that the absolute temperature of the ring is reduced by a factor of approximately four from room temperature (300 K). In this temperature range, the electrical resistivity of aluminium decreases by approximately a factor of ten [11]. The induced

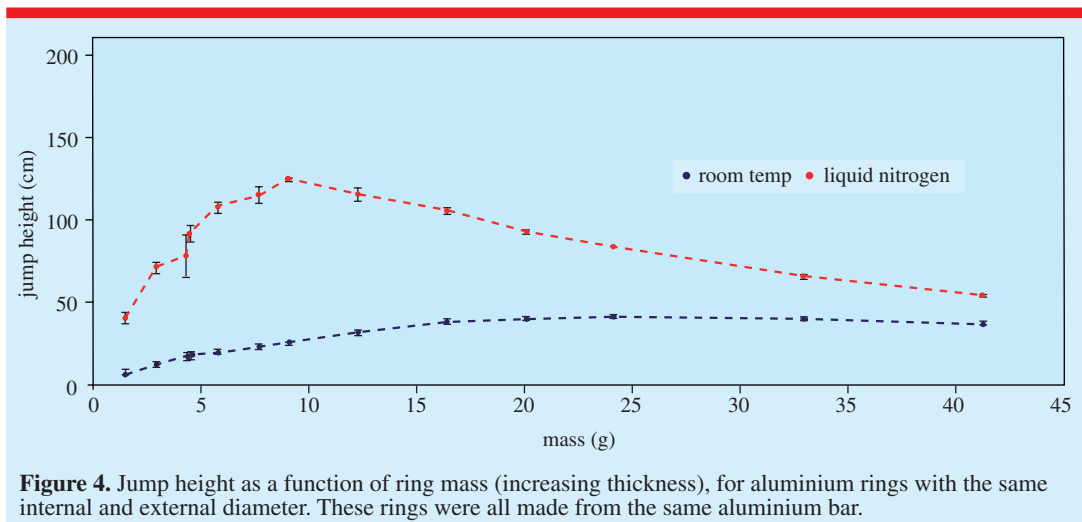


Figure 4. Jump height as a function of ring mass (increasing thickness), for aluminium rings with the same internal and external diameter. These rings were all made from the same aluminium bar.

current in the ring will therefore increase by a factor of about ten; hence one should expect a substantial increase in the jump height for a ring chilled to liquid nitrogen temperatures, which is indeed observed. None of the above standard theoretical arguments can explain why PJF's replacement ring performed so poorly compared to the lost original.

Experimental method

The experiments were performed by placing the ring to be tested on to the wooden coil former which was situated in front of a ruler fixed to the wall behind. The current through the solenoid was switched on, resulting in an instantaneous jump of the ring. It is important to appreciate that the solenoid current should be switched off immediately after the jump has occurred to avoid burning out the coil. Through preliminary observation, the ball-park area of the jump was noted, enabling a video camera to be focused on the area so as to accurately determine (to within about half a centimetre) the maximum height obtained. For the low-temperature trials, the same procedure was followed, but this time the ring was cooled in liquid nitrogen contained in a shallow polystyrene box and then quickly transferred to the wooden former using tongs².

² Extreme care must be taken when using liquid nitrogen. Safety goggles and gauntlets must be worn. It is important to remember that the ring will still be very cold after it has reached the floor and again must be picked up using the tongs.

Experiments were also performed in an attempt to understand the major factors affecting the jump height of aluminium rings. The first set of experiments explored what happens when the geometry (thickness and both the inner and outer diameters) of the rings was varied. A second investigation looked at the effect of different metallurgical states. These were attained by varying the annealing time and temperature.

Results

Varying ring dimensions

A set of rings of varying mass was produced. The mass was varied by making rings of different thickness while keeping the same inner and outer diameters. The results of this investigation are shown in figure 4. Clearly, at temperatures close to that of liquid nitrogen, there is a well-defined maximum jump height corresponding to an optimum mass to produce this effect. The response is much flatter at room temperature and the maximum (as well as can be detected) occurs in rings of higher mass. The reasons for this are not well understood.

Metallurgical considerations

Different rates of cooling have a significant effect on the particle size of materials. Within metals, the particle size corresponds to the size of individual domains separated by grain boundaries and dislocations. Rapid cooling, also referred to as quenching, is associated with small particle

size, while slow cooling, known as annealing, results in larger particles. Small particles occur in quenching because the temperature is reduced at such a rate that there is insufficient time for the atoms to arrange themselves into the ideal crystal lattice structure. This is because they still hold enough thermal energy to overcome energy potentials within the material and thereby can undergo migration.

During annealing, the temperature, and therefore the thermal energy of the atoms, is reduced gradually, allowing the atoms to arrange themselves into a more idealized lattice. Annealing results in a lower resistance than quenching due to the smaller number of defects formed. Grain boundaries and surfaces can be viewed as defects because they cause a break in the perfect structure of the crystal lattice. The presence of other defects, such as impurities, will also result in an increase in resistance, caused by the distortion of the crystalline structure within the material. This will affect the flow of electrons, as well as the orientation of atoms, making direct collisions more likely [12].

By suitable annealing of an aluminium ring we were able to reduce its electrical resistance such that the jump height was similar to that observed in PJF's original ring. This fulfilled one of the major aims of this investigation.

It is interesting to note that although the effects of heat treatment of metals had been known to blacksmiths for thousands of years, understanding of this only began in the early 1930s at about the same time as physicists were beginning to understand the structure of the atomic nucleus.

Discussion

A feature of the jumping ring is that it lends itself to experimental investigation and development. In the original apparatus, both the number of turns and the gauge of the wire used in the solenoid were arbitrary—we had a large unwanted reel of wire, which had been lying around in the laboratory for many years. However, it would be interesting to see the effect of varying these parameters. Likewise, in the original apparatus, a large number of iron wires was used to increase the flux linkage to the ring. It would be useful to see how the jump height of the ring is affected by a solid iron core, and cores of different heights and diameters.

Early investigations [1] used rings of different materials. Copper is likely to provide an interesting comparison with aluminium and some preliminary work has already been carried out. Because copper has a density which is roughly three times that of aluminium, a ring of comparable dimensions will be three times as heavy. The electrical resistivity of copper and aluminium at 77 K are within about 10% of each other. The combined effect can have dramatic consequences. PJF once gave a lecture at IOP Publishing at Dirac House, Bristol, UK where he demonstrated the jumping ring experiment using a copper ring. At low temperatures this jumped to a height of some two metres, and following Newton's laws of motion, it landed on the glass surface of an overhead projector standing nearby, smashing the glass. This did not increase his popularity with IOP Publishing, but the lecture has been well remembered ever since. The lower mass of an aluminium ring may well not have smashed the glass of the overhead projector.

Conclusion

The jumping ring experiment is a memorable demonstration of the laws of electromagnetic induction which invariably proves popular when shown to audiences. It can be constructed with ease using materials which are readily available. Finally, it lends itself to investigation and, as such, is a suitable topic for student projects.

Note added in proof. Since submitting this article an interesting analysis of the jumping ring experiment has been given by Bostock-Smith [13].

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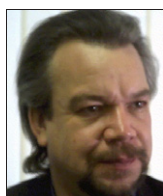
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Peter Ford retired from the Physics Department of the University of Bath in 2007. He was awarded an MBE for 'services to higher education and to science' in the 2008 Queen's New Year Honours List.



Gary Mathlin lectures in the Department of Physics at the University of Bath and is currently Undergraduate Admissions Tutor.



Mel Baylie graduated from the Department of Physics at the University of Bath in 2007. She is currently working for BAE Systems on their Commercial Graduate Scheme based at the Warton Aerodrome in Lancashire, UK.



Charlotte Palmer graduated from the Department of Physics at the University of Bath in 2007. She is currently studying for her PhD in laser plasma interactions at Imperial College London, UK.