# Electromagnetic Radiation from the acceleration of charged particles

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**ABSTRACT**

*Charged particles are held to radiate as a function of their acceleration in some situations. One well-known exception to this is in atomic structures, and some believe that classical electromagnetism cannot be used to describe atomic behaviour because it requires that an electron radiates energy under acceleration. This is naive, for if accelerating charges radiate under some conditions but not others, every complete model of the universe must be able to predict precisely which behaviour occurs in new situations, or accept that that model of the universe cannot be complete. This paper examines the problem in general terms. It does not claim to be original in every detail, but is a summary of the problems associated with accelerative radiation.*

**Keywords:** Electromagnetic, radiation damping, accelerative radiation, retarded time, Larmor Formula.
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## INTRODUCTION

The concept that charged particles radiate electromagnetic energy seems to have arisen in an attempt to describe how X-rays arise, in Röntgen's discovery of 1895 [1]. With the Thompson plum-pudding model of the atom the electrons were believed to smack into the plum pudding and stop dead [2]. With this model the only possible explanation for the X-radiation was that the extreme deceleration during the impact had generated the radiation. This became so embedded in the scientific consciousness that ever since there has been little critical analysis of whether it does in fact occur. The first challenge to this concept came with the evolution of the theories on relativity, which developed from 1900 onwards, marked particularly by Einstein's 1905 paper [3]. The next challenge came in 1911, when Rutherford proposed a new model of the atom as a positive central charge orbited by negatively charged electrons [4]. This paper shows how these ideas impact the concept of accelerative radiation.

## MATERIALS AND METHODS

**Applying Relativity to linear accelerative radiation**
Consider an experiment where an electron is accelerated from the observer's rest frame, up to a velocity $v$, then is decelerated back into the observer's rest frame. Assume further that the acceleration produces radiation.
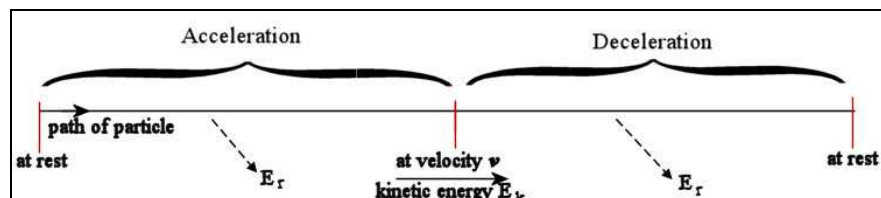


**Figure 1**

The work 'U' supplied in accelerating it to velocity $v$ will be the change in kinetic energy $E_k$ of the electron, *plus* any energy radiated $E_r$ during the acceleration, so $U=E_k+E_r$. The radiated energy is generated by extra work supplied

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if the Principle of Conservation of Energy is to apply. This radiation escapes from the system. Thus we have supplied $E_k+E_r$, and are left with the kinetic energy $E_k$ after $E_r$ escapes. Next decelerate the electron so that it comes back to rest in the observer's rest frame. Relativity states that from the electron's frame of reference it is simply undergoing more acceleration, albeit in a different direction. We therefore see that the work done, and supplied to the observer's rest frame, is again $E_k+E_r$ because the electron radiates under the new deceleration, increasing the work done to 'accelerate' it into the original rest frame. The radiation again escapes leaving the electron at rest in the observer's rest frame.

Hence the work done in the observer's rest frame in the first step is $U=E_k+E_r$, while that same amount of work $U=E_k+E_r$ is returned to that frame in the second step. There is no net work done in that frame, but $2E_r$ escapes the system, being generated in excess. The process either violates the Principle of Conservation of Energy and an accelerating charged particle is a source of free energy, or $E_r$ must be zero – that is, there is no accelerative radiation. Therefore if accelerative radiation exists we can create a source of infinite energy by simply having a charged particle bounce back and forth between charged endplates, radiating energy as it does so.

For accelerative radiation, when the particle is being accelerated by an outside force momentum considerations would require it to be radiated more or less in the direction of acceleration, to increase the work done by the force providing the acceleration. By contrast, for a particle to "slow down" by itself purely as a result of radiative loss, energy must be radiated in opposition to the acceleration in order to conserve momentum. Relativity does not allow us to pick and choose like this, so this is another aspect of the dichotomy at the heart of the concept.

**Applying Relativity to circular accelerative radiation**
Consider a thought experiment where an electron is orbiting round a positively-charged central point as shown in Figure 2. This approximates the condition of an electron in an atom. The question is "Does Classical Electromagnetism demand that the electron radiates and thereby loses kinetic energy, spiralling into the central charge?"
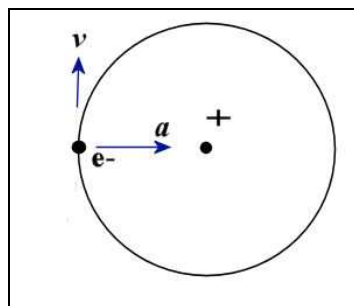


**Figure 2**

The electron is orbiting because centripetal acceleration changes its path from a linear one to a curved one. It's orbital velocity is $v$, its centripetal acceleration is $a$, and for it to slow down and spiral into the central charge radiation must be emitted broadly in line with $v$ so that it might carry momentum away from the electron.

Consider things from the electron's instantaneous reference frame – it is in this frame that the electron accelerates. The electron sees a force causing acceleration to the right in Figure 2. For deceleration to occur the electron must emit radiation in the forward orbital direction (in line with $v$). This is not only at right angles to the acceleration $a$, but in one specific direction out of the 360 degrees of possible directions that are normal to $a$; there is no mechanism whereby the electron, from its own reference frame, can work out what direction is required. Taking it further, suppose the electron was not in orbit, but simply accelerating towards the positive charge; this idea would have the radiated energy at one specific right angle, causing the electron to start orbiting.

If instead we apply the results of the previous section on linear acceleration, but still assume the radiation occurs, the work done in radiating the energy must be provided by an increased centrifugal force, so the electron would orbit at lower speed for any specific distance from the central charge. It would not fall into the central charge, but emit radiation continuously towards it. Hence in this model we would see continuous radiation coming from atomic structures and a consequential violation of the Principle of Conservation of Energy.

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**Possibility of an underlying flaw**
This all implies a fundamental flaw in the concept. Accelerative radiation is assumed to be a "lossy" or "damping" mechanism that takes energy away from the accelerating charge. Comparison with damping in classical mechanics is instructive. Take a simple resonant system involving a mass and a spring as shown in Figure 3a. The spring is fixed at one end to an inertial reference, and at the other to a mass. The mass oscillates up and down on the spring.
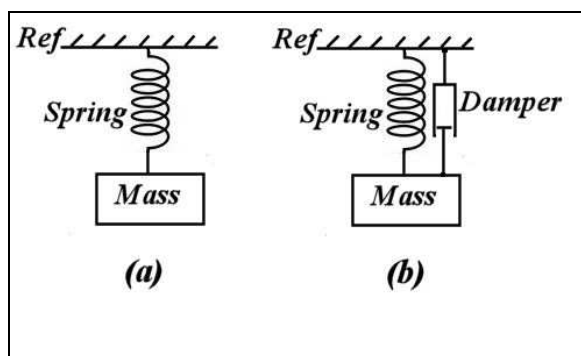


**Figure 3**

When the system is oscillating the spring provides a force which is a function of its *position* with respect to the reference. The mass provides a force that is a function of its acceleration or deceleration, *the second derivative of position*. The two components together will oscillate indefinitely. There is no loss associated with the acceleration of any part of the system. How do we make the system lossy? We add a component that is a function of the first derivative of position – namely, velocity. This is called a damper or a friction component, and the forces generated are a function of velocity. This is shown in Figure 3b. By implication, for losses to occur in electron acceleration there should be sensitivity to velocity. However, any accelerative radiation is a function of the electron's acceleration in its own reference frame; it is always travelling at zero velocity in its own reference frame and so such radiation cannot be lossy. Consequently any radiation emitted cannot act to remove energy from the system.

**Examples**
In order to better consider the matter, a few examples are given here of mechanisms that have been or are claimed to give rise to accelerative radiation.

1. X-rays
2. Dipole radiation
3. Electron Spirals in Cloud Chamber
4. Cyclotron radiation

**Example 1: X-rays**
As already mentioned, accelerative radiation was the only way to explain X-rays with the plum-pudding model of the atom. With the Rutherford model of the atom it became possible to describe the radiation as an interaction between the electron and the powerful fields inside atoms. The presence of K-shell radiation in the X-ray spectra confirmed this view; here, an incoming electron knocked a k-shell electron out of an atom and produced characteristic radiation as another electron fell into that shell to replace it.

**Example 2: Dipole Radiation**
This is readily modelled by Maxwell's Equations [5] [6]. It is easiest to consider the radiation from a dipole antenna as being a two-stage process coupling the near-field where the effect of moving charges dominates, to the far-field where radiation dominates. The first stage can be thought of as consisting of four induction phases making up one wavelength as shown in Figure 4.

1. The voltage across the ends of the dipole is momentarily zero, and the current flow is at its peak positive value; this induces a peak magnetic field around the antenna, but no electric field.
2. The current drops to zero as the voltage reaches its peak positive value; this induces a peak positive electric field across the ends of the antenna, but the induced magnetic field drops to zero.
3. The current falls further to its peak negative value as the voltage across the antenna falls to zero; this induces a peak negative magnetic field around the antenna but the electric field drops to zero.
4. The current rises again to zero as the voltage reaches its maximum negative value; the induced magnetic field rises to zero as the induced electric field reaches its negative peak.
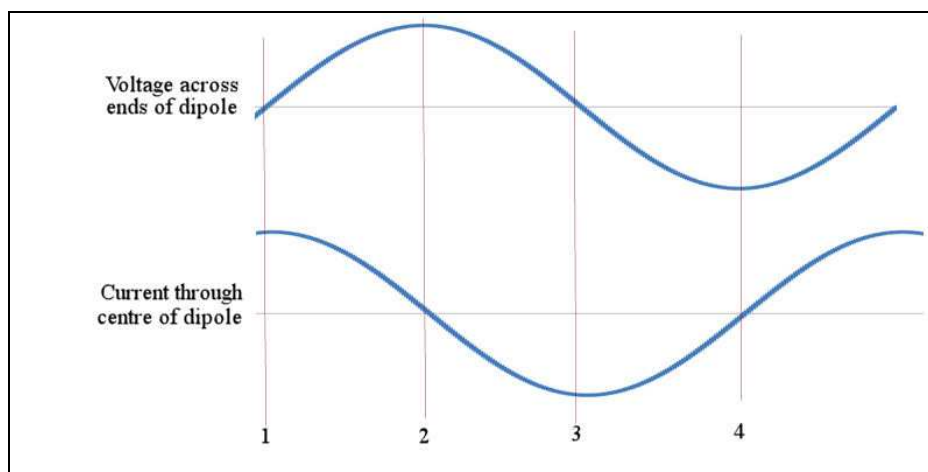
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**Figure 4**

Thus in the "near-field" region around the antenna the electric fields are simply those of the charges bunched at the ends of the antenna, and the magnetic fields are simply those of moving charges. Items placed in this near field are therefore electromagnetically coupled to the charges moving in the antenna and thereby to the antenna drive source as in a transformer; placing anything that can absorb electromagnetic energy near the antenna therefore presents a load to it. If this were all that happened the antenna would not radiate and would have infinite impedance to its driving circuits, merely storing energy in the alternating fields. Maxwell's insight was that the changing fields in this region gave rise to free radiation. Hence the four phases above are expanded as follows:-

1.    At this point although the induced electric field is zero, it is changing at its fastest rate, giving rise to a peak in the radiated wave magnetic energy through the displacement term. The magnetic field is at a peak, but momentarily stationary, so there is no radiated wave electric field.
2.    At this point the current is changing at it fastest rate, so the induced magnetic field is changing at its fastest rate, giving rise to a peak in the radiant displacement electric field. The electric field is momentarily stationary so the radiated displacement magnetic field falls to zero.
3.    At this point although the *induced* electric field is zero, it is again changing at its fastest rate, here giving rise to a peak in the radiant displacement magnetic field. The magnetic field is at a peak, but momentarily stationary, so there is no radiant electric field.
4.    At this point the current is changing at it fastest rate, so the *induced* magnetic field is changing at its fastest rate, giving rise to a peak in the radiant displacement electric field. The electric field is momentarily stationary so the radiant displacement magnetic field is zero.

This radiating displacement energy drives the "far-field" radiation and puts a work load on the induction field, so that the antenna impedance is reduced because it absorbs electrical energy from the transmitter power source in order to restore this loss. This radiation energy is not coupled to the source, and unlike the near field anything placed in the far-field has no effect on the antenna although it may have a localised effect on the radiation pattern.

Although the velocity of the moving charges in the antenna is relevant to the induced magnetic field, Maxwell's equations describe nothing that radiates as a function of charge acceleration. There have been claims that radiation from accelerating charges drives the far field radiation pattern in antenna, but:-
• These equations do not use Maxwell's equations and are unable to derive antenna impedances or to be used in antenna design.
• There is no mechanism to select a particular radiant frequency.
• They cannot describe the distinctive near-field characteristics that are observed.

As such they do not match the completeness and proofs of Maxwell's equations.

**Example 3: Electron Spirals in Cloud Chambers**
In 1912 CTR Wilson designed the cloud chamber to detect energetic charged particles. Charged particles take spiral paths in cloud chambers, as shown in Figure 5. The path of the particle is curved by an external magnetic field, and is made visible because its ionisation trail creates condensation centres in a gas super-saturated with water vapour. The magnetic field is normal to the paper in Figure 4.
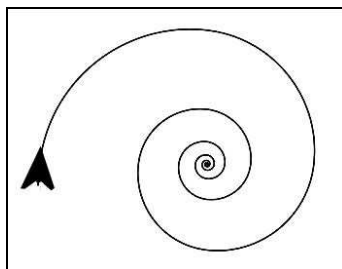
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**Figure 5**

This has been used to suggest that the charged particle is radiating energy because of its centripetal acceleration and that is why it spirals to a stop. However, a superconducting ring dropped into a magnetic field will float on that magnetic field because of the opposing current induced in the ring. The current will flow for as long as the ring is left in the field. This contradicts the suggestion.

In fact the ionisation trail is made up of a series of minor impacts between the fast-moving particle and air molecules that ionise those air molecules and absorb a tiny amount of kinetic energy from the particle. Thus the particle slows down a little on each collision, creating a spiral path as it loses its kinetic energy. This provides an explanation that does not conflict with the observations concerning the superconducting ring.

**Example 4: Cyclotron radiation**
The cyclotron was invented by Leo Szilárd and the first one came into service in Berkeley in 1932. A cyclotron accelerates charged particles to high speeds guiding them along a spiral path from a source near the centre of the machine to a target at the periphery. It consists of a magnetic field designed to contain the moving particles in a circular path. The particles move in a vacuum container within the poles of a magnet, and this contains two D-shaped electrodes; these D-electrodes are hollow with the path of the particles passing inside them. As the particles pass from one electrode to the other an alternating voltage is applied in-phase with them to produce acceleration. This is shown in Figure 6, with the electrodes in red and the path of the particles in black.
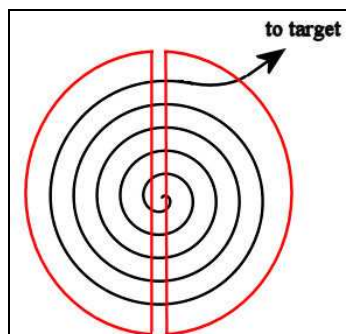


**Figure 6**

The particles are injected at the middle and accelerate as they spiral outwards; they will have some mechanism at the periphery to draw them out of the cyclotron towards a target. The magnetic field is normal to the page in Figure 6.

Undesirably, the particles lose energy by radiation. The centripetal acceleration around their path does not have any effect on the frequency of the radiation, which is odd if the radiation is indeed caused by the acceleration. By tuning the particle's speed a weak magnetic field can give the same acceleration as a strong one, but the loss frequencies will be different. On the other hand adjusting the magnetic field strength directly affects the radiation frequency. So is there another explanation? First consider a particle passing through a magnetic field

If a charged particle enters a magnet with its magnetic dipole aligned with that of the magnet then the particle will be accelerated by the attraction between it and the magnet, creating a reduction in magnetic energy in the composite particle/magnet system when it is inside the magnet; when it leaves the magnet it will be slowed down by that same attraction to its original velocity as the magnetic energy is restored. No radiation so far and no loss of energy. But what if the particle enters the magnetic field with its magnetic dipole in opposition to the magnetic field as shown in Figure 7?
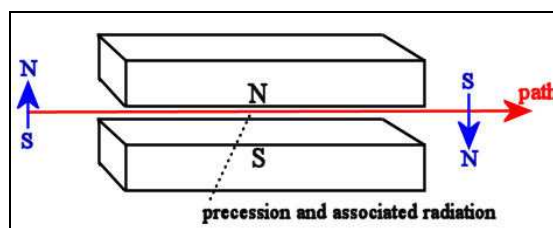
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**Figure 7**

Here the path of the particle is shown in red, and the orientation of the particle's dipole is shown in blue. On entry from the left the north poles will repel each other, as will the south poles, and the particle decelerates as the kinetic energy is converted to increased magnetic energy in the combined particle/magnet system. While between the poles of the magnet the particle precesses into alignment with the field, causing radiation as the magnetic energy is dissipated; the surplus energy in the magnetic field is converted to a deficit of equal magnitude. As it leaves to the right the particle's south pole is now attracted to the magnet's north pole and vice-versa as the magnetic field is recharged to its resting level, so the particle is slowed down further. Even if the particle's dipole is only a little out of alignment with the magnetic field, it will press towards to full alignment and exit the magnet at a lower velocity than it entered.

The next question is of course *"is there anything that will perturb the perfect alignment of the particle dipole with the magnetic field?"* for if there is no misalignment then there can be no precessional radiation or energy loss. The first source of misalignment is granularity in the magnet, causing localised perturbations in the field. As such, the charged particles will precess into new alignments with each twitch of magnetic field orientation and lose speed at each misaligned boundary. Another source of field misalignment is the gap between the electrodes that causes fringing fields shown diagrammatically in red below.
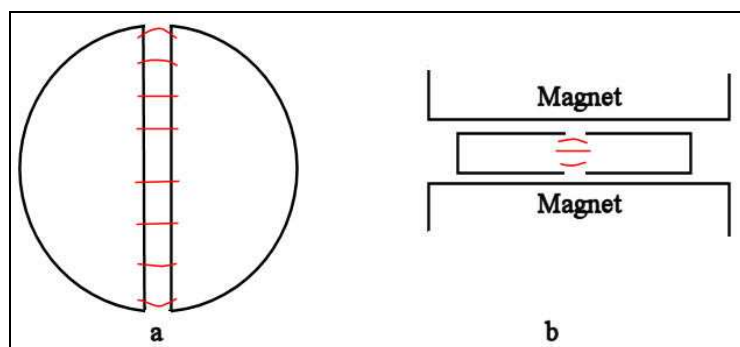


**Figure 8**

Figure 8a shows the top view of the fringing, while Figure 8b shows a horizontal section. First, Maxwell's equations show that as the particles travel between the electrodes the fringing electric fields induce mis-oriented magnetic fields in the rest frame of the particles. Second, they further show that as the electric field changes across its cycle these changes cause displacement magnetic fields. The former component increases with drive voltage and particle velocity, while the latter increases with drive voltage and drive frequency. Hence there is a mix of magnetic fields some of which have the potential to reorient the particle's dipole and hence radiate energy even with the most precise construction and beam guidance. Indeed, it is difficult to see how one might suppress such fields, so particles in a cyclotron *must* lose energy by magnetic resonance. Of course, this does not of itself prove that it does not also lose energy by accelerative radiation, but that violates energy conservation and there would appear to be no need for such a mechanism.

**Generic Theories of Accelerative Radiation**
Many theories of accelerative radiation are based on the concept of "retarded time", and are often related to the Larmor Formula [7]. In these theories, a charged particle at rest has a perfectly symmetrical radial electrostatic field. However, if we take changes in the electric field to be propagated at the speed of light, and we apply force to the centre of the particle to accelerate it, then transverse field components appear in the field at a radial distance from the centre. These then radiate. However:-

• The transverse field component is an intrinsic part of the field structure, albeit distorted by acceleration. If it is lost by radiation there will be a net loss of the energy of the charged particle's electric field. An electron would no

longer be an electron, but something less, with a reduced electric charge; enough acceleration and the entire charge on the electron would dissipate into radiation.

• This energy is assumed to radiate, yet this is a fixed electric field and to radiate it must convert into displacement electric and magnetic fields. Such mechanisms are not generally identified..

• None of these theories is able to derive any characteristic frequency for the radiation, yet in almost every case examined characteristic frequencies appear. The theories seem incomplete. One would also expect such radiation to be massively broadband as it is lacking an energy transition mechanism.

## CONCLUSION

A charged particle undergoing acceleration cannot radiate energy purely as a consequence of that acceleration without violating the Principle of Conservation of Energy. The concept of accelerative radiation from charged particles may have no validity in an energy-conserving universe, and therefore in Classical Electromagnetism. If this is so, the fact that electrons orbiting inside atoms do not radiate presents no problem to Classical Electromagnetism.

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