Larmor Precessions as Charge Pumps

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There is currently great interest in generating dc currents via spin dynamics. This comes from the emerging science of *spintronics* where research efforts are directed towards new means for investigating spin dynamics and development of new spin sources. Not surprisingly these efforts concentrate on *spin* transport, used as a digital signal, which offers lower losses than the dissipative *charge* transport used in modern computers. However spin dynamics can also influence charge transport, which has a wider application than computing. With global issues forcing new interest in sustainable energy sources, the prospect of power generation from quantum spin is appealing and worthy of serious consideration. Only in recent years has science demonstrated the realization of pumping electrons 'uphill' (i.e. against a potential gradient) in what has been called *quantum ratchets*. Currently such systems are considered more as a scientific curiosity than a potential power source since the power levels are very low. In this paper we consider a much more powerful form of quantum ratchet, electron precession acting as a charge pump.

A precessing electron acts like a tiny precessing bar magnet creating a magnetic field rotating at the Larmor frequency. Such a moving field will by Faraday's law $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ impart an impulsive force e**E** on a nearby itinerant conduction electron, where **v** is the velocity of the field **B** at that electron position. Since the magnitude of **v** is proportional to the precession frequency, which for electron precession is typically in the microwave region, this Larmor-charge coupling (LCC) is quite strong. Generally, in conductors, the LCC is randomised in amplitude and direction so that its only contribution to electron transport is a thermal one. However a team at the University of Manitoba, Canada (Gui et al[1]) has recently found that Larmor precession *can* produce electrical current, as reported in Hu et al[2]. This work used a ferromagnetic conductor (Permalloy) where the precessing electrons were those responsible for its permeability, i.e. they were fixed in the crystal lattice. An applied static magnetic field supplied the precession axis and also (taking account of the geometric demagnetising factor) determined the centre precession frequency. Microwave power was fed to the Permalloy so as to phase lock the precessions at the FMR resonance. The surprising fact that, internally within a ferromagnetic conductor, Larmor microwaves can be rectified to produce DC, should be noted.

In some respects this work is similar to the calculations of Durst et al[3], supported by experiments discussed in Shi et al[4], where a 2D electron gas is immersed in a static magnetic field while also being irradiated with microwaves. The gas exhibits negative conductivity (i.e. DC current generation) when the microwave frequency is close to the electron cyclotron frequency. The microwaves act as a charge pump where the rectification comes from the co-operative phase of the microwaves against the cyclotron movement. Somehow there is a spatial-temporal coherence between the incoming microwaves and the helical path travelled by conduction electrons that favours microwave pumping in one direction. However there is one important difference. In Durst's[3] work the *external* microwaves are the source for the power extracted via the DC current, whereas in Gui[1] the charge pumping comes from the Larmor precessions, or more precisely from the *internal* microwaves generated by those precessions. This distinction is important, here we have evidence that Larmor precession can be harnessed as a quantum energy source.

Sceptics will argue that in Gui's[1] work an external microwave source is necessary to phase lock the precessions, and this could be the real source of DC electrical power, that energy extracted from the precession via LCC must be replenished via the incident microwaves. However the Gui[1] calculations do not include this incident microwave pumping, they use the weak Rashba spin-orbit interactions from the Larmor precessions. Also there is evidence[5] from work performed by Hans Coler over 80 years ago (see below) that Larmor precessions in magnetized Fe can self organise to produce a DC current effect.

If we wish to use Larmor precessions as charge pumps, but without external microwaves maintaining the FMR resonance, we need another method for cohering the precessions. There is an argument that, in a ferromagnetic conductor, phase locking of the individual lattice precessions can be achieved by spin-spin coupling to and from conduction electrons, the conduction electrons themselves must precess and could therefore transport phase across the lattice. The new science of spintronics is producing interesting data that supports this view, such as the fact that a current of spin polarised conduction electrons can effect magnetization, can flip precessing lattice electrons to their higher energy state, see[6]. Perhaps of more significance is the work reported in March 2007 Meeting of the American Physical Society, Session B2: Spin Transfer-Driven Magnetic Excitations[7], where spontaneous FMR magnetic oscillations excited by DC currents of spin polarized electrons are described. This strongly suggests that a current of spin-polarized electrons can perform the desired task of RF synchronization, i.e. of inducing ferromagnetic resonance over multi atom domains, more importantly over the conduction electron's mean free path. It may be noted that magnetized Fe, as used by Coler, is a good material for producing spin polarised conduction electrons.

For this coherence coupling to be effective, the line width of the precession frequencies must be small, hence this requires (a) high purity ferromagnetic material and (b) high uniformity of the bulk magnetization. Both of these features would apply to the Stromerzeuger devised by Hans Coler[5]. This remarkable device produced more DC power output than input, as verified in 1926 by three German Professors. Coler used iron rods, situated within a coil structure that very likely compensated for the usual demagnetisation effect, producing uniform magnetization over a significant length of each rod. It can be shown that, using high purity iron having very high permeability, and with cylindrical symmetry, the magnetization becomes uniform over a significant working volume.

Magnetization precession is usually modelled by either the Landau-Lifschitz equation, which includes a damping term introduced in a phenomenological way by an additional torque acting at right angles to the gyro-magnetic torque, or the Landau-Lifschitz-Gilbert equation where the damping is a viscous term using the Gilbert damping coefficient. These equations model the known decay processes that take place within magnetization precession which, in the absence of a RF sustaining field, reduces to zero. It is observed that there are two mechanisms for this damping, each having its own time constant. One is the natural de-phasing brought about by the fact that the electrons have a spread of Larmor frequencies, the second is de-phasing due to lattice thermal vibrations. *However we know that the individual electron precessions do not decay, quantum rules do not allow that, the individual precession* *energies remain intact*, perhaps “dissipation” is the wrong word to describe this type of damping. The microscopic nature of this apparent dissipation in ferromagnetic materials is still not clear and is currently the focus of considerable research. With regard to Coler’s observed absolute negative conductance, an explanation for this based on internal pumping from these persistent Larmor precessions now seems feasible.

The anomalous over-unity performance witnessed by the Professors in 1926 was a puzzle to them (but they all agreed that the iron rods were the anomalous source), so much so that, fearing for their reputations, they did not want their findings publicised. Now, some 80 years later, our modern view of spintronics demystifies that result. In the interests of our planet’s future, now is the time for Coler’s discovery to be re-invented.

References.

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