Electrodynamic force law controversy

Peter Graneau
205 Holden Wood Road, Concord, Massachusetts 01742

Neal Graneau
Department of Engineering Science, Oxford University, Parks Road Oxford OX1 3PJ, United Kingdom

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Cavalleri *et al.* [Phys. Rev. E **58**, 2505 (1998); Eur. J. Phys. **17**, 205 (1996)] have attempted to resolve the electrodynamic force law controversy. This attempt to prove the validity of either the Ampère or Lorentz force law by theory and experiment has revealed only that the two are equivalent when predicting the force on part of a circuit due to the current in the complete circuit. However, in our analysis of internal stresses, only Ampère's force law agrees with experiment.

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Cavelleri *et al.* [1] have drawn attention to the debate between the experimental validity of the original law of electrodynamics proposed by Ampère [3] in 1822 and the magnetic component of the modern Lorentz force law, also referred to as the Biot-Savart law. There is universal agreement that both laws agree on the magnitude and direction of the force between two separate current carrying circuits. However the controversy has concentrated on the predictions of both laws when investigating forces generated in a single circuit. Cavalleri *et al.* [2] in an earlier paper, have derived the fact of complete equivalence between the two laws when performing the specific calculation of the self-force on part of a current loop.

However the conflict between the two laws does not arise in experiments that simply measure the force on part of a circuit such as performed by Cavalleri *et al.* [1] One needs to perform measurements of the internal reaction force distribution in an isolated current loop to find where the conflict occurs. When the circuit is a rigid metallic conductor, then this reaction force distribution becomes the stress distribution, which strains atomic bonds between lattice ions. Stress, by definition, can only be determined by calculating forces of attraction and repulsion between pairs of atoms across a stress interface. Cavalleri *et al.* [1,2] did not perform the appropriate calculation, which is only possible with Ampère's law, and hence failed to appreciate the difference between the two electrodynamic force laws.

This point was emphasized in the two experimental papers [4,5] that are referenced in Ref. [1]. A clear demonstration of the crucial difference between the two laws will therefore focus on the magnitude and location of the recoil forces as well as the motion of the mobile conductor section. The recoil measurement was neglected in the experiment performed by Cavalleri *et al.* [1].

In 1982, Peter Graneau performed a similar experiment at MIT [6]. He also calculated the predictions of the Ampère and Lorentz laws for the force on a mobile part of the circuit and found that they agree with each other and the experimental findings. Hence Cavalleri *et al.* [1,2] did not discover any new facts and further, failed to pick an experiment that could lead to different predictions from the two laws.

The circuit chosen for the MIT experiment [6] was a long rectangle, meant to represent a railgun (see Fig. 1). Force measurements were performed on the short mobile side, known in railgun terminology as the projectile or armature. The electrical connections between the armature and the fixed parts of the circuit were made with liquid mercury cups, just as in the Cavalleri *et al.* [1] experiment. Both force laws predict that when dc or ac current flows through the circuit, the armature will be accelerated in the direction away from the short side containing the connections to the power supply, normally referred to as the railgun breech. The measured magnitude of the force was found to be given with

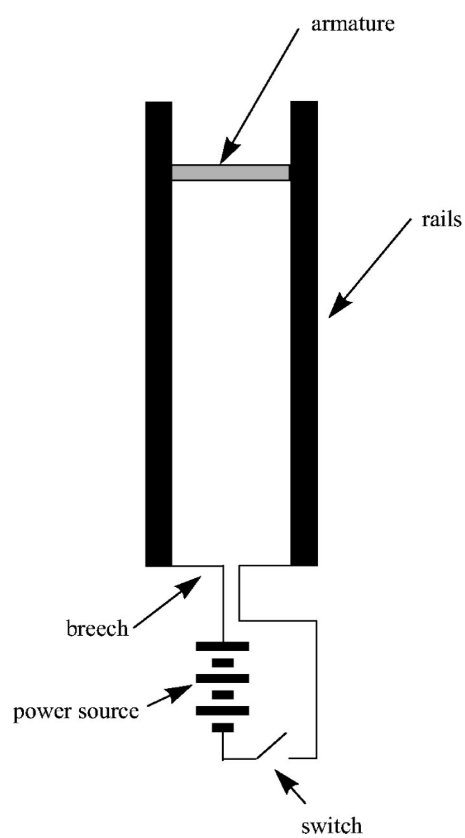

FIG. 1. Schematic depiction of the main features of a railgun.

equal accuracy by an integral of the Lorentz and the Ampère force formulas.

The distinction between the two force laws is only revealed by an investigation of the seat of the recoil forces. The Ampère electrodynamics predicts that the rails are pushed back longitudinally by the armature toward the breech of the railgun. As a result of the very large forces developed in railguns being developed for the military [7,8], the rails are likely to buckle and deflect laterally with severe consequences to the progress of the projectile, which is required to slide between the rails.

Contrary to the nonlocal Ampère electrodynamics, the Lorentz recoil forces are local forces and the recoil is felt by the electromagnetic field surrounding the armature. Modern relativistic electromagnetism [9] proposes that the electromagnetic energy travels between the rails from the power source to the armature and the cause of the Lorentz force on the armature is the transference of the field energy momentum to the electrons in the metal. The recoil force corresponding to the armature acceleration must therefore cause the deceleration of the incoming field energy. In other words, the rails will not feel the recoil action at all. This is a natural consequence of a law that predicts that electrodynamic forces are always completely perpendicular to the current in the conductor with zero longitudinal component. Railgun designers have therefore adamantly ignored the possibility of rail recoil forces that has contributed to their failure to produce efficient railgun accelerators [7]. It is an instance where ignorance of the force law controversy has certainly led to wasteful research and development expenditure.

The 1982 paper [6] already furnished some experimental evidence of longitudinal rail recoil action. Further proof was provided with a specific rail buckling experiment [8]. European railgun researchers [10] have also confirmed the Ampère rail recoil mechanism. These practical experiences provide a basis to decide which of the two laws more accurately describes observable electrodynamic forces. Thus the force law controversy is resolved in favor of Ampère's force law, which Maxwell [11] called ''the cardinal formula of electrodynamics.'' Many other experiments, relevant to the resolution of the force law controversy, are described and reviewed in two books [12,13], which also include experimentally verified extensions of the Ampère-Neumann electrodynamics.

[1] G. Cavalleri, G. Bettoni, E. Tonni, and G. Spavieri, Phys. Rev. E **58**, 2505 (1998).

[2] G. Cavalleri, G. Spavieri, and G. Spinelli, Eur. J. Phys. **17**, 205 (1996).

[3] A. M. Ampère, *Théorie Mathématique des Phénomènes Électrodynamiques Uniquement Déduite de l'Expérience* (Blanchard, Paris, 1958).

[4] P. T. Pappas, Nuovo Cimento Soc. Ital. Fis., B **76**, 189 (1983).

[5] T. E. Phipps and T. E. Phipps, Jr., Phys. Lett. A **146**, 6 (1990).

[6] P. Graneau, J. Appl. Phys. **53**, 6648 (1982).

[7] P. Graneau and N. Graneau, IEEE Trans. Magn. **33**, 4570 (1997).

[8] P. Graneau, J. Appl. Phys. **62**, 3006 (1987).

[9] R. Feynman, *Lectures on Physics* (Addison-Wesley, Reading, MA, 1964), Vol. 2, pp. 27–29.

[10] M. Löffler, *Proceedings of the Symposium on Electromagnetic Launch Technology, Celle, Germany, 1993* (ETHZ, Zurich, 1993).

[11] J. C. Maxwell, *A Treatise on Electricity and Magnetism* (Oxford University, London, 1881), Vol. 2, p. 175.

[12] P. Graneau, *Ampère-Neumann Electrodynamics of Metals* (Hadronic, Palm Harbor, FL, 1985).

[13] P. Graneau and N. Graneau, *Newtonian Electrodynamics* (World Scientific, Singapore, 1996).