# Ampère's Hairpin Spaceship

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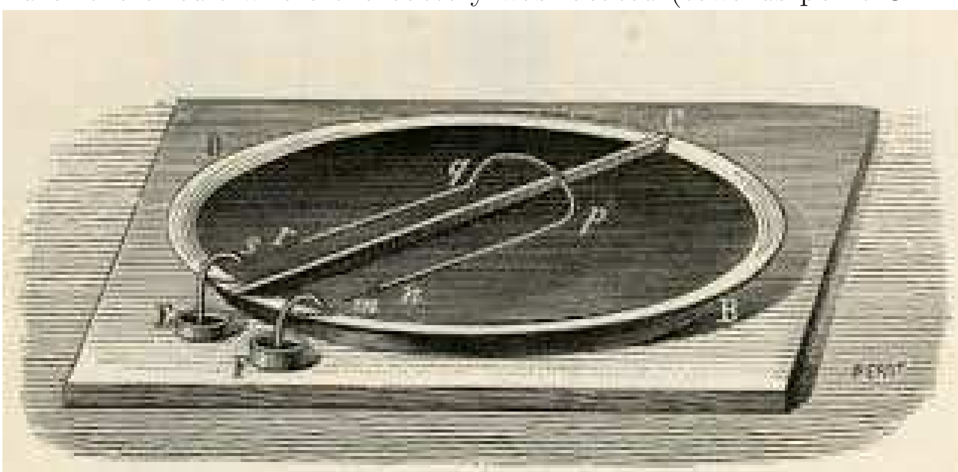
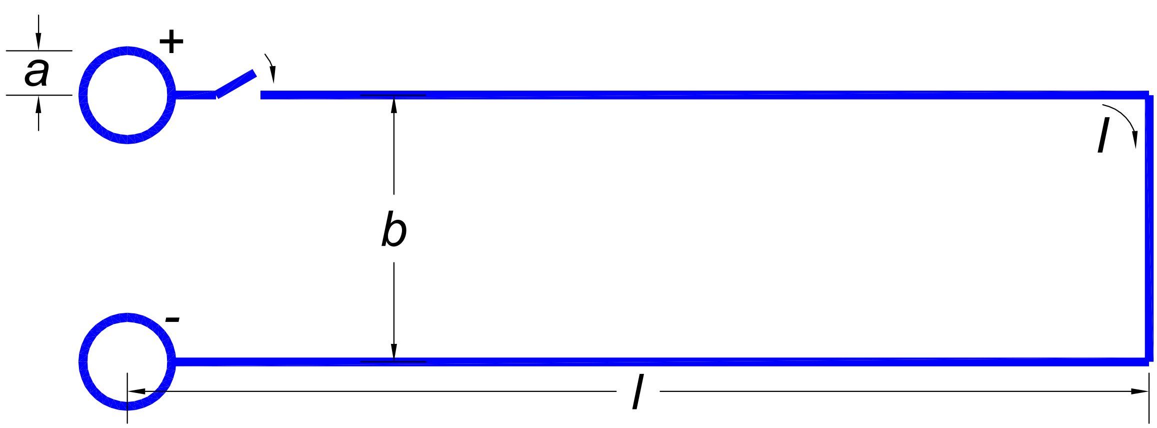
## 1 Problem

In 1822, Ampère and de La Rive [1] conducted an experiment, illustrated below, in which a conducting "hairpin" *npqr* floated on two troughs of mercury that were connected to the two terminals of a Voltaic pile (battery). The floating hairpin was observed to move away from the end of the circuit where the battery was located (towards point C in the figure).



Consider the variant shown below in which a U-shaped wire of radius $r_0$, length $l$, width $b \ll l$ and electrical resistance $R$ is connected to a capacitor made from two conducting spheres of radii $a \ll b$ with initial charges $\pm Q_0$. Discuss the motion of the system (assumed to be a rigid body) after the switch is closed and the capacitor discharges.



## 2 Solution

Ampère's hairpin experiment, considered as the first railgun, is discussed in [2].

The variant sketched on the previous page is an $R$-$L$-$C$ circuit, whose switch is closed at time $t = 0$. The circuit equation for the current $I = -\dot{Q}$ is,

$$0 = L\dot{I} + RI + \frac{Q}{C} = L\ddot{Q} + R\dot{Q} + \frac{Q}{C}, \tag{1}$$

whose solution depends on whether $R^2$ is larger or smaller than $4L/C$.

The resistance $R$ is typically much less than 1 Ohm, which is much less that $1/30c$ where $c$ is the speed of light ($3 \times 10^{10}$ cm/s) in Gaussian units, which are employed below.

The capacitance of a conducting sphere of radius $a$ is just $a$ (in Gaussian units), so the capacitance of two spheres in series is $a/2$ in the first approximation. See sec. 2(a) of [3] for the next approximation, and [4] for a discussion of higher approximations.

To estimate the self inductance, we take the spheres be centered at $(x, y, z) = (0, \pm b/2, 0)$, and the crosspiece of the hairpin to be at $(l, -b/2 < y < b/2, 0)$, with $l \gg b \gg a \gg r$. Then, the magnetic field in the plane $z = 0$, between the $x$-segments and away from their ends, is approximately that associated with infinite-length wires,

$$B_z(b \ll x \ll l - b, -b/2 + r_0 < y < b/2 - r_0, 0) \approx -\frac{2I}{c(b/2 + y)} - \frac{2I}{c(b/2 - y)}\,. \tag{2}$$

The self inductance of the circuit is related to the magnetic flux $\Phi$ through it according to $\Phi = cLI$. Supposing the field (2) holds for $0 < x < l$, the magnetic flux is, with $y' = y - b/2$,

$$\Phi \approx 2\int_{r_0}^{b} \frac{2I}{cy'}\, l\, dy' = \frac{4lI}{c} \ln\frac{b}{r_0}, \tag{3}$$

and the self inductance $L$ is approximately (see Art. 685 of [5] for a slightly better approximation),

$$L = \frac{\Phi}{cI} \approx \frac{4l}{c^2} \ln\frac{b}{r_0}\,. \tag{4}$$

Thus, $4L/C \approx (16l/ac^2)\ln(b/r_0) \gg 1/c^2 \gg R^2$, since $l/a \gg 1$, $b/r_0 \gg 1$ and $R^2 < 1/900c^2$. In this case, the time dependence of the charge $Q$ on the capacitor has the form,

$$Q(t > 0) = Q_0\, e^{-Rt/2L} \left(\frac{R}{4L\omega} \sin\omega t + \cos\omega t\right) \approx Q_0\, e^{-Rt/2L} \cos\omega_0 t, \tag{5}$$

noting that $4L/C \gg R^2 \Rightarrow 1/LC \gg R^2/4L^2$, and,

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \approx \sqrt{\frac{1}{LC}} \equiv \omega_0 \gg \frac{R}{2L}\,. \tag{6}$$

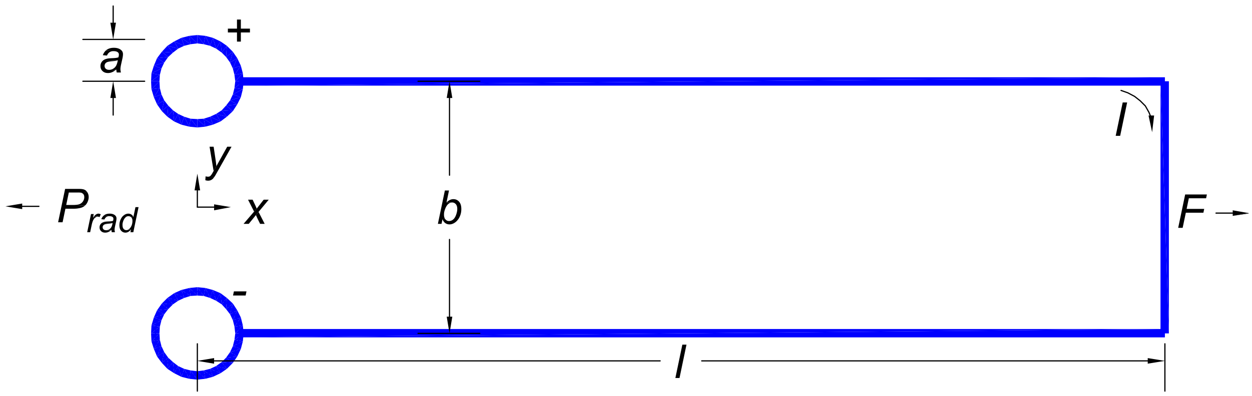
The time dependence of the current is,

$$I(t > 0) = -\dot{Q}(t > 0) \approx Q_0\, e^{-Rt/2L} \left(\frac{R}{2L} \cos\omega_0 t + \omega_0 \sin\omega t\right) \approx Q_0\omega_0\, e^{-Rt/2L} \sin\omega_0 t, \tag{7}$$

which obeys $I(0) = 0$.

## 2.1 Self Force on the Hairpin

The magnetic field due to the current $I$ exerts a Lorentz force on itself, with an $x$-component on the crosspiece (and no net force in the $y$- and $z$-directions).[1]




At the crosspiece, where $x = l$, the $z$-component of the magnetic field is approximately one half of that given by eq. (2) because the $x$-currents only for $x < l$. That is,

$$B_z(l, -b/2 + r_0 < y < b/2 - r_0, 0) \approx -\frac{I}{c(b/2+y)} - \frac{I}{c(b/2-y)}\,. \tag{8}$$

The Biot-Savart-Lorentz force on the crosspiece is then approximately,

$$F_x^{\rm c} = -\int_{-b/2+r_0}^{b/2-r_0} \frac{IB_z(x_{\rm c}, y, 0)}{c}\, dy \approx \frac{2I^2}{c^2} \ln\frac{b - r_0}{r_0} \approx \frac{2I^2}{c^2} \ln\frac{b}{r_0}\,, \tag{9}$$

supposing that the wire radius $r_0$ is small compared to the separation $b$.[2]

In addition, the changing magnetic field associated with the changing current leads to an electric field that act on the charges on the capacitor. As we are mainly interest in the $x$-component of the force, $QE_x$, we compute $E_x = -\partial A_x/\partial ct$ via the vector potential (ignoring effects of retardation),

$$A_x(0, b/2, 0) \approx \int_a^l \frac{I\, dx}{cx} - \int_a^l \frac{I\, dx}{c\sqrt{x^2+b^2}} = \frac{I}{c}\ln\frac{l}{a} - \frac{I}{c}\ln\frac{l + \sqrt{l^2+b^2}}{a + \sqrt{a^2+b^2}} \approx \frac{I}{c}\ln\frac{b}{2a}\,, \tag{10}$$

for $a \ll b \ll l$. The vector potential at the spheres is mainly due to the current near the spheres, and so is largely independent of the length $l$ of the hairpin.

The force on the positively charge sphere is then, recalling eqs. (5) and (7),

$$F_x^+ = -\frac{Q}{c}\frac{\partial}{\partial t}A_x(0, b/2, 0) \approx -\frac{QQ_0\omega_0^2\, e^{-Rt/2L}\cos\omega_0 t}{c^2}\ln\frac{b}{2a} = -\frac{Q^2\omega_0^2}{c^2}\ln\frac{b}{2a}\,. \tag{11}$$

[1]That is, the Lorentz force does not obey Newton's third law (of action and reaction), which this problem was chosen to illustrate.

Note also that the U-shaped wire is electrically neutral, and so is an "isolated" current element in the sense of Ampère. For such elements the force laws of Ampère and Biot-Savart-Grassman-Lorentz are not equivalent, and the Lorentz force law is the correct on to use. See, for example, [2] for further discussion of these force laws.

[2]Note that even as the current $I$ changes sign when the capacitor discharges, the force is always in the $+x$ direction.

The force $F_x^-$ on the negatively charged sphere is the same as that of eq. (11) since $A_x(0, -b/2, 0) = -A_x(0, b/2, 0)$. The total $x$-force on the system is largely independent of the length $l$ of the hairpin,

$$F_x = F_x^{\rm c} + F_x^+ + F_x^- \approx \frac{2I^2}{c^2} \ln \frac{b}{r_0} - \frac{2Q^2\omega_0^2}{c^2} \ln \frac{b}{2a} \,. \tag{12}$$

Since $r_0 \ll a$, $F_x$ is positive.

A circuit of mass $m$ takes on final $x$-velocity,[3]

$$v_f = \frac{1}{m} \int_0^\infty F_x \, dt \approx \frac{2}{mc^2} \frac{Q_0^2}{2RC} \left( \ln \frac{b}{r_0} - \ln \frac{b}{2a} \right) = \frac{2U_0}{mc^2} \frac{1}{R} \ln \frac{2a}{r_0} \,, \tag{13}$$

where $U_0 = Q_0^2/2C$ is the initial electric energy stored in the capacitor. The final velocity is largely indpendent of the length $l$ and width $b$ of the hairpin, so long as $a \ll b \ll l$.

The final momentum of the circuit is,

$$P = mv_f \approx \frac{1}{c^2} \frac{Q^2}{RC} \ln \frac{2a}{r_0} = \frac{2U_0}{c^2} \frac{1}{R} \ln \frac{2a}{r_0} \,. \tag{14}$$

Noting that a resistance $R$ in Gaussian units is the resistance in Ohms divided by $30c$,

$$\frac{v_f}{c} \approx \frac{60}{R[\Omega]} \frac{U_0}{mc^2} \ln \frac{2a}{r_0} \,. \tag{15}$$

"Practical" values of the parameters can be chosen such that $v_f$ is roughly the escape velocity of the Earth (11 km/s $\approx 3 \times 10^{-4} c$).

## 2.2 Radiation of Momentum

The nonzero momentum acquired by the hairpin as the capacitor discharges is balanced by an equal and opposite increase in the electromagnetic field momentum,[4] whose density is related by,

$$\mathbf{p}_{\rm EM} = \frac{\mathbf{E} \times \mathbf{B}}{4\pi c} = \frac{\mathbf{S}}{c^2} \tag{16}$$

where $\mathbf{S}$ is the Poynting vector [7]. In some cases, the field momentum remains close to the sources of the electromagnetic fields [8, 9], and in quasistatic examples where the field momentum is nonzero the equal and opposite "mechanical" momentum is often characterized as "hidden" [10]. However, in the present example the electric charge and current densities go to zero with time, and hence so do the near electromagnetic fields and any electromagnetic

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[3] $\int_0^\infty I^2 \, dt \approx Q_0^2 \omega_0^2 \int_0^\infty e^{-Rt/L} \sin^2 \omega_0 t \, dt = \frac{Q_0^2}{2LC} \int_0^\infty e^{-Rt/L} (1 - \cos 2\omega_0 t) \, dt = \frac{Q_0^2}{2LC} (\frac{L}{R} - \frac{R/L}{R^2/L^2 + 4/L^2C^2})$ $\approx \frac{Q_0^2}{2RC}$. Simlarly, $\int_0^\infty Q^2 \omega_0^2 \, dt \approx Q_0^2 \omega_0^2 \int_0^\infty e^{-Rt/L} \cos^2 \omega_0 t \, dt = \frac{Q_0^2}{2LC} \int_0^\infty e^{-Rt/L} (1 + \cos 2\omega_0 t) \, dt$ $= \frac{Q_0^2}{2LC} (\frac{L}{R} + \frac{R/L}{R^2/L^2 + 4/L^2C^2}) \approx \frac{Q_0^2}{2RC}$.

[4] Field momentum of the form (16) was first discussed by J.J. Thomson [6].

field momentum temporarily stored in the near fields. Rather, the field momentum is radiated away, and the present example is a kind of antenna problem [11, 12].[5]

The attempt below to model the radiation via analytic approximations is, however, not very satisfactory.

To compute the radiation of momentum by the hairpin as it discharges, we make the approximation that its bulk motion can be neglected, although for extreme parameters this is not a good approximation. We follow sec. 66 of [14] in noting that the radiation (far zone) fields can be deduced from the vector potential $\mathbf{A}$ according to,

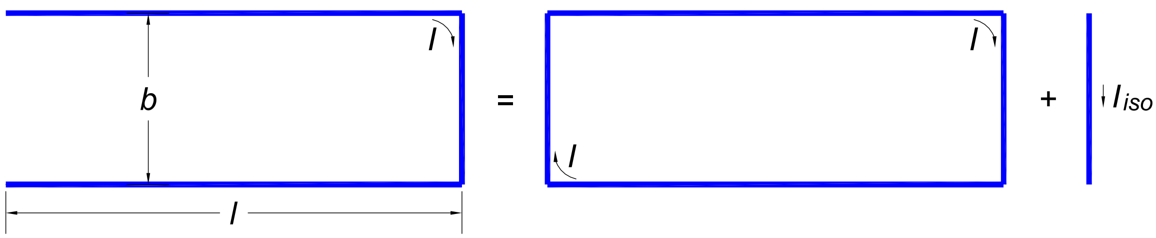
$$c\,\mathbf{B}(\mathbf{r},t) = \left[\dot{\mathbf{A}}\right] \times \hat{\mathbf{r}}, \qquad c\,\mathbf{E}(\mathbf{r},t) = \hat{\mathbf{r}} \times \left(\hat{\mathbf{r}} \times \left[\dot{\mathbf{A}}\right]\right), \tag{17}$$

where,

$$\left[\dot{f}(\mathbf{r},t)\right] = \frac{\partial}{\partial t} f(\mathbf{r}, t - r/c), \tag{18}$$

is the time derivative at the retarded time $t' = t - r/c$.

The vector potential depends on the current in the three segments of the hairpin, which are equivalent to a closed current loop plus an isolated current element that flows from $(0, b/2, 0)$ to $(0, -b/2, 0)$.




The closed loop is a magnetic dipole of moment $\mathbf{m} = -(Ibl/c)\,\hat{\mathbf{z}} = -(Qbl/cRC)\,\hat{\mathbf{z}}$, centered at $(l/2, 0, 0)$, while the isolated current element has a vector potential in the far zone,

$$\mathbf{A}_{\rm iso}(\mathbf{r},t) = \int \frac{[I]}{cr}\, d\mathbf{l} \approx -\frac{b\,[I]}{cr_{\mathbf{d}}}\,\hat{\mathbf{y}} = -\frac{b\,[Q]}{cr_{\mathbf{d}}\,RC}\,\hat{\mathbf{y}} = -\frac{[\mathbf{d}]}{cr_{\mathbf{d}}\,RC} = \frac{\left[\dot{\mathbf{d}}\right]}{cr_{\mathbf{d}}}, \tag{19}$$

where the approximation holds for observers far from the hairpin, $\mathbf{d} = Qb\,\hat{\mathbf{y}}$ is its electric dipole moment. and $r_{\mathbf{d}} = r$ is the distance to the observer from the center $(0,0,0)$ of the isolated current element. Altogether, the vector potential is that due to the electric dipole moment $\mathbf{d}$ and the (perpendicular) magnetic dipole moment $\mathbf{m}$. The radiation fields then follow from eq. (71.4) of [14] as,

$$\mathbf{B}_{\rm rad} = \frac{\left[\ddot{\mathbf{d}}\right] \times \hat{\mathbf{r}}_{\mathbf{d}}}{c^2 r_{\mathbf{d}}} + \frac{\hat{\mathbf{r}}_{\mathbf{m}} \times (\hat{\mathbf{r}}_{\mathbf{m}} \times [\ddot{\mathbf{m}}])}{c^2 r_{\mathbf{m}}} = \frac{e^{-[t]/RC}}{c^2 R^2 C^2} \left\{ Qb \frac{\hat{\mathbf{y}} \times \hat{\mathbf{r}}}{r} + \frac{Qbl}{cRC} \frac{\hat{\mathbf{z}} - (\hat{\mathbf{r}}_{\mathbf{m}} \cdot \mathbf{z})\,\hat{\mathbf{r}}_{\mathbf{m}}}{r_{\mathbf{m}}} \right\}, \tag{20}$$

$$\mathbf{E}_{\rm rad} = \frac{\hat{\mathbf{r}}_{\mathbf{d}} \times \left(\hat{\mathbf{r}}_{\mathbf{d}} \times \left[\ddot{\mathbf{d}}\right]\right)}{c^2 r_{\mathbf{d}}} - \frac{[\ddot{\mathbf{m}}] \times \hat{\mathbf{r}}_{\mathbf{m}}}{c^2 r_{\mathbf{m}}} = \frac{e^{-[t]/RC}}{c^2 R^2 C^2} \left\{ Qb \frac{-\hat{\mathbf{y}} + (\hat{\mathbf{r}} \cdot \mathbf{y})\,\hat{\mathbf{r}}}{r} + \frac{Qbl}{cRC} \frac{\hat{\mathbf{z}} \times \hat{\mathbf{r}}_{\mathbf{m}}}{r_{\mathbf{m}}} \right\}, \tag{21}$$

where $\mathbf{r}_{\rm m} = \mathbf{r} - l/2\,\hat{\mathbf{x}}$ is the vector from the center of the magnetic dipole to the observer. We are interested in the radiated momentum, whose density is proportional to $\mathbf{E} \times \mathbf{B}$. However, it is "well known" that the radiation patterns of "simple" dipoles are symmetric and no net momentum is radiated by such dipoles alone. In the present example, radiation of momentum is associated only with the cross terms,

$$\begin{aligned}
\mathbf{p}_{\rm rad} &= \frac{\mathbf{E}_{\mathbf{d}} \times \mathbf{B}_{\rm m}}{4\pi c} + \frac{\mathbf{E}_{\mathbf{m}} \times \mathbf{B}_{\rm d}}{4\pi c} \\
&= \frac{Q^2 b^2 l\, e^{-2[t]/RC}}{4\pi c^6 r r_{\rm m} R^5 C^5} \{-\hat{\mathbf{x}} + (\hat{\mathbf{r}}_{\rm m} \cdot \hat{\mathbf{x}})\,\hat{\mathbf{r}} - (\hat{\mathbf{r}}_{\rm m} \cdot \hat{\mathbf{z}})\,\hat{\mathbf{r}}_{\rm m} \times \hat{\mathbf{y}} + (\hat{\mathbf{r}} \cdot \hat{\mathbf{y}})\,\hat{\mathbf{r}} \times \hat{\mathbf{z}} \\
&\qquad - (\hat{\mathbf{r}} \cdot \hat{\mathbf{y}})(\hat{\mathbf{r}}_{\rm m} \cdot \hat{\mathbf{z}})\,\hat{\mathbf{r}} \times \hat{\mathbf{r}}_{\rm m} + (\hat{\mathbf{z}} \cdot \mathbf{r} \times \hat{\mathbf{r}}_{\rm m})\,\hat{\mathbf{y}}\}.
\end{aligned} \tag{22}$$

[5]For a review of the related topic of rocket propulsion by lasers, see, for example, [13].

In the limit that $l = 0$, such that $\mathbf{r} = \mathbf{r}_{\rm m}$, we find,

$$\begin{aligned}\mathbf{p}_{\rm rad} &= \frac{Q^2 b^2 l\, e^{-2[t]/RC}}{4\pi c^6 r r_{\rm m} R^5 C^5} \{-\hat{\mathbf{x}} + \cos^2\theta_x\,\hat{\mathbf{x}} + \cos\theta_x\cos\theta_y\,\hat{\mathbf{y}} + \cos\theta_x\cos\theta_z\,\hat{\mathbf{z}} \\ &\qquad\qquad - \cos\theta_x\cos\theta_z\,\hat{\mathbf{z}} + \cos^2\theta_z\,\hat{\mathbf{x}} - \cos\theta_x\cos\theta_y\,\hat{\mathbf{y}} + \cos^2\theta_y\,\hat{\mathbf{x}}\} \\ &= 0. \end{aligned} \tag{23}$$

And, to the first approximation, use of $\mathbf{r}_{\rm m} = \mathbf{r} - l/2\,\hat{\mathbf{x}}$ does not lead to a nonzero radiation momentum in the $-\mathbf{x}$ direction. Presumably the various approximation used above are too simplistic to clarify the momentum balance in this example.

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