X-RAYS AND X-RAY APPARATUS

AN ELEMENTARY COURSE

BY

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New York

THE MACMILLAN COMPANY

1924

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THE MACMILLAN COMPANY
NEW YORK · BOSTON · CHICAGO · DALLAS
ATLANTA · SAN FRANCISCO

MACMILLAN & CO., LIMITED
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"The details of knowledge which are important will be picked up *ad hoc* in each avocation of life, but the habit of the active utilisation of well-understood principles is the final possession of wisdom."

(WHITEHEAD.)

PREFACE

For some years the writer has been giving courses of lectures to medical students on the physical principles underlying the use of X-rays and other radiations. While these have not been received with any greater enthusiasm than that which medical students are wont to display towards anything savouring of physics, they have served to strengthen the conviction that the application of any branch of science cannot be successfully taught, or understood, without a knowledge of fundamental principles. The science of medicine becomes more and more an application of the laws of physics, chemistry and biology, in consequence of which the problem of medical education is no easy one. Applications, moreover, continually change, sometimes, indeed, overnight, and yet the medical student must be familiar with advances in his profession. What is he or his teacher to do? To train only specialists is no solution, for even if we assume that all students have the necessary qualifications to be so trained (which is doubtful), it will be admitted that even a specialist must begin with a broad foundation. While the opinion of a physicist on such a question may be worth but little, it does seem to the writer that there should be an insistence on the kind of teaching which drives home the broad basic principles of the fundamental sciences. The student with a real grasp of principles fears no application.

In this book, therefore, an attempt has been made to present as clearly and as simply as possible the physical principles utilized in the field of radiology. While applications are discussed to a considerable extent, the emphasis is on the fundamental conceptions without a grasp of which no intelligent practice or progress in this field is possible. It is hoped that the book will fill a need as a basis of instruction in the physical end of X-ray work, both in medical schools and in hospitals. As only a very elementary knowledge of physics has been assumed, it is hoped, too, that it may make an appeal to those medical practitioners in whose college days the curriculum did not include the subject of radiology.

The author has pleasure in taking this opportunity of expressing his gratitude to all those who gave assistance in the preparation of the book; in particular, to my colleague, Dean A. L. Clark, for helpful suggestions; to the authorities of Queen's University for placing at my disposal many facilities to expedite routine work; to Dr. Duane of Harvard University for permission to reproduce graphs; and to my wife for help with the index and general assistance throughout the preparation of the manuscript. For the gift or loan of electrotypes my sincere thanks are due Dr. W. D. Coolidge, the Wappler Electric Co., the Victor Electric Corporation, the International X-ray Corporation, the Waite and Bartlett Manufacturing Co., Geo. W. Brady & Co., and Mr. P. D. Ross of Stanford University. Most of the line diagrams were drawn by Mr. E. Harris of Queen's University and to him, too, I desire to express my appreciation.

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Queen's University,
Kingston, Canada,
July 21, 1924.

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CHAPTER I

THE INTERRUPTERLESS TRANSFORMER

1. To operate any type of x-ray bulb, a high voltage must be applied to the terminals of the bulb. By "high" is meant a voltage which is many times greater than any of those ordinarily available. To be more definite, a dry cell of the type familiar to everybody, has a voltage between its terminals of about 1.4 volt, while a small storage battery has a value of about two volts. Between the lead wires which deliver electric power to the average householder, the common voltage is 110, although by special arrangement a supply of 220 volts may be obtained. But before useful x-rays may be obtained from a bulb, voltages of the order of 20,000 or very much higher must be used. There are on the market machines making available 300,000 volts. How are these high values obtained?

At least three different types of machines have been used for this purpose: (1) the "electrostatic" electric machine, such as the Wimshurst; (2) the transformer; (3) the induction coil. The first type is of scarcely more than historical interest in these days of powerful x-ray outfits, and need not be considered in this book. It is highly desirable, however, that every user of an x-ray bulb be familiar with the second and the third types and each of these will be discussed in detail. Both are based on two important fundamental principles: first, that of electro-magnetism; second, that of electro-magnetic induction. Before proceeding to an explanation of these, a few simple electrical terms will be defined.

2. **The volt** is a unit of electrical pressure, or speaking more scientifically, of difference of potential. Voltage or difference of potential is always necessary before any current can flow, just as difference of pressure is necessary before water will flow along a pipe. Voltage, however, is not current any more than water pressure is the volume of water flowing per second.

Voltages available may be one of two types, (1) D.C. (direct current), where the polarity never reverses, (2) A.C. (alternating current), where the direction is continually reversing. A dry cell has a voltage of 1.4 (D.C.), while the ordinary house is generally supplied with 110 (A.C.).

The **ampere** is the practical unit of current and has to do with the quantity of electricity flowing past any point in a circuit per second. To make the matter more concrete, when 110 volts are applied to a 20 watt tungsten lamp, a current of about one-fifth of an ampere is flowing through the lamp; when a 600 watt electric iron is joined to the 110-volt lighting circuit, a current of from 5 to 6 amperes is flowing through the iron. The voltage causes the flow but the current (again the quantity of electricity passing a point per second) depends both on the voltage and on the opposition to the flow between the points to which the voltage is applied—that is, it depends also on the resistance. To use a water analogy once more, water pressure causes a flow but the quantity of water flowing per second through a pipe depends both on the water pressure and on the size of the pipe.

A **rheostat** is a simple device for altering the amount of wire in an electric circuit, that is, of varying the resistance and, therefore, of regulating the magnitude of the current (within limits).

In Figure 1, if the movable arm AB is in position I, the current flows through coils 1 and 2; if the arm is moved to position II, the current must flow through coils 1, 2, 3, 4, that is, against a greater amount of resistance. Hence the current in the second case is smaller.

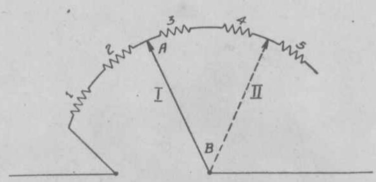

FIG. 1.—A simple rheostat, with five coils.

A **milliampere** is just one-thousandth of an ampere. As will be seen later, the current flowing through the primary of an x-ray transformer is measured in amperes, possibly as high as 30, while the current through the x-ray bulb itself is such a small fraction of an ampere that its magnitude is invariably given in milliamperes (ma).

THE PRINCIPLE OF ELECTRO-MAGNETISM

3. Most readers are familiar with the fact that when a small bar magnet is placed beneath a sheet of paper, and iron filings are sprinkled on it, the filings arrange themselves along regular lines somewhat as represented in Figure 2 (an actual photograph). This simple experiment indicates that in the whole region around the magnet there is what is called a magnetic field of force. To visualize this field we generally say that it is traversed by magnetic lines of force, the closeness of the lines of force at any particular place being a measure of the strength of the magnetic field at that place. These lines of force are closed curves leaving the North pole of a magnet, entering the South pole and we say there is a magnetic flux through the magnet. Indeed, whenever magnetic lines are passing through any region, we speak of a magnetic flux through that region.

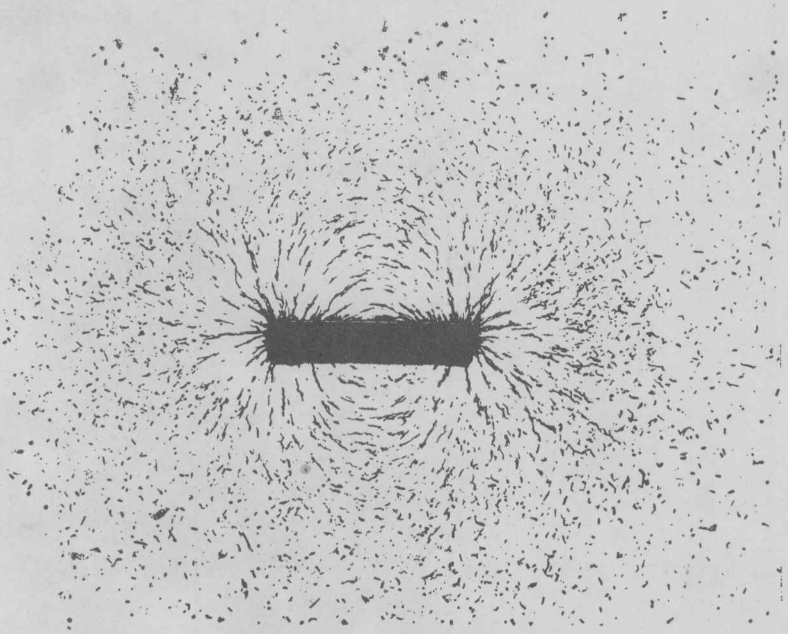

Fig. 2.—Iron filings about a bar magnet.

Suppose, now, that the wire AB (Fig. 3) is carrying a current of several amperes, and we sprinkle iron filings on a sheet of paper through which the wire passes. We find that, so long as the current is flowing, the filings are arranged in circular lines with the wire as center. *A magnetic field, therefore, surrounds a wire carrying a current.* This is the fundamental principle of electro-magnetism. *We can have magnetic fields subject to the control of an electric current.* If a wire carrying a current is wound

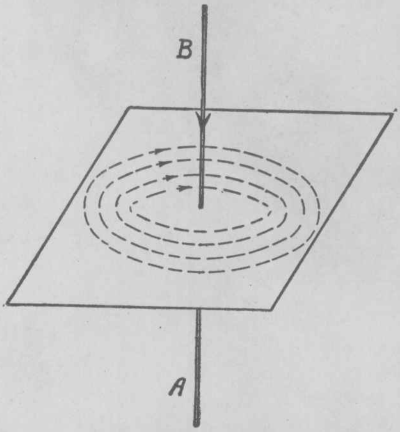

Fig. 3.—Circular lines of force encompass a wire carrying a current.

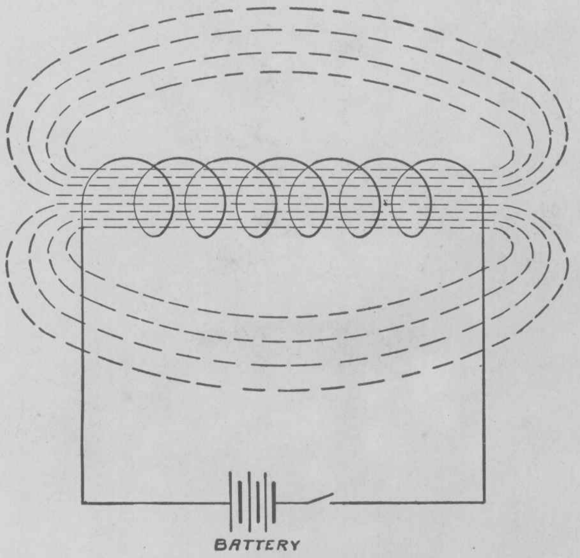

FIG. 4.—Lines of force are linked with a solenoidal coil carrying a current.

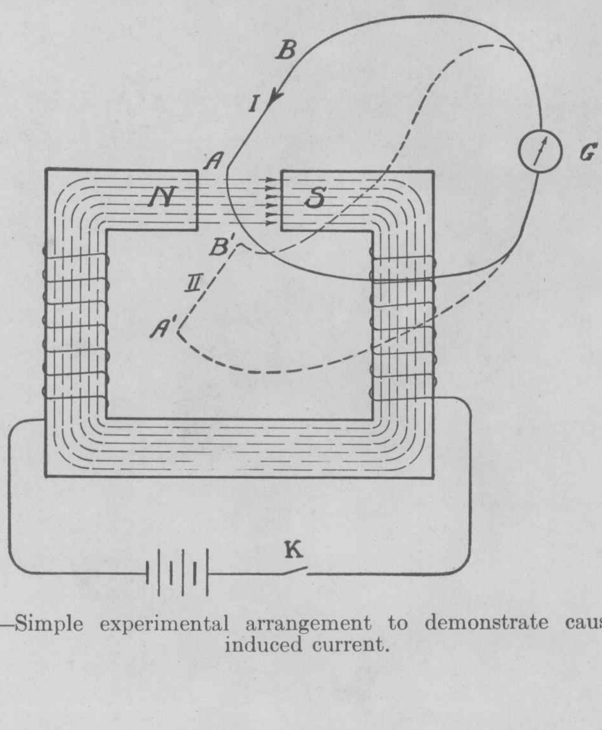

FIG. 5.—Simple experimental arrangement to demonstrate cause of an induced current.

into what is called a solenoid (Figure 4) it can easily be shown that one end of the solenoid acts as the North, the other end as the South pole of a bar magnet with magnetic lines of force somewhat as represented in the figure. Obviously these lines are linked with the electric circuit, and at once disappear when the electric circuit is broken. If the air inside the coil be replaced by soft iron, the soft iron becomes strongly magnetized under the influence of the magnetic field due to the current, and the number of lines of force may be increased many times. We have in fact an electro-magnet. Break the circuit, the lines of force disappear; make the circuit, the lines of force are introduced. Electro-magnets are frequently of the shape illustrated in Figures 5 and 6.

The Principle of Electro-Magnetic Induction

4. This may best be explained by reference to one or two simple experiments. Suppose we are provided with an electro-magnet of the type illustrated in Figure 5 (where the lines of force are again represented by dotted lines). Imagine, also, a simple electric circuit containing a wire AB which may be readily moved, a current-measuring instrument G, *but no cell or battery or other source of voltage.* Suppose next the switch K controlling the electro-magnet circuit is closed and in this experiment left so. If, now, the wire AB is moved from position I across the lines of force to position II (A′B′) a momentary current will be indicated by G, the measuring instrument. If the wire be moved back again, a momentary current in the opposite direction is recorded. In general, it will be found that as long as the wire is cutting the lines of force, there is a current whose direction depends on the direction of motion of the wire. Such a current is called an induced current, the voltage causing it, an induced E.M.F. (electro-motive force). *Whenever, therefore, a portion of any circuit is moving with reference to magnetic lines of force, there is*

an induced E.M.F. (voltage) in that portion of the circuit, and if that circuit is closed a current results. This is the very important principle of electro-magnetic induction.

The principle may be stated in another and possibly more useful way. This will be evident from another look at Figure 5. When the movable wire is in position AB, there are no lines of force linked with this circuit, but when it is in position A′B′, all the lines of the electro-magnet are linked or interlocked with it. We frequently say, therefore, that an induced voltage results in an electric circuit whenever there is any *change* in the number of lines of force linked or interlocked with it. To emphasize this, we shall perform another experiment. Imagine the movable wire in position A′B′. If, now, the electro-magnet circuit (which we shall call the *primary*) is *broken,* a momentary induced current results in the movable wire circuit, which we shall call the *secondary.* Again when the primary circuit is *made,* a momentary current in the opposite direction results in the secondary. In this experiment, the secondary circuit is not moved, but the magnetic lines of force either disappear or reappear. There is therefore relative motion of magnetic lines and a portion of a circuit, and so an induced current results. Putting it in the other way, at "break" of the primary, there is a decrease in the number of lines linked with the secondary; at "make" an increase—in both, a change, and an induced voltage results.

Magnitude of Induced Voltage

5. This involves a consideration of two other points. (1) If the wire AB (Figure 5) be moved from position I to position II at two different rates, for example, one ten times faster than the other, it will be found that the induced current is just ten times as great, although it will, of course, last for a correspondingly shorter time. In other words, the magnitude of an induced voltage depends on the *rate*

at which the change in the number of linkings takes place. The faster the change, or the more quickly lines are cut, the higher the induced voltage. (2) If the secondary circuit be altered as represented in Figure 6, so that the magnetic lines of force link the circuit twice, it will be found that on "break" of the primary circuit the induced voltage is twice that obtained previously. If the secondary

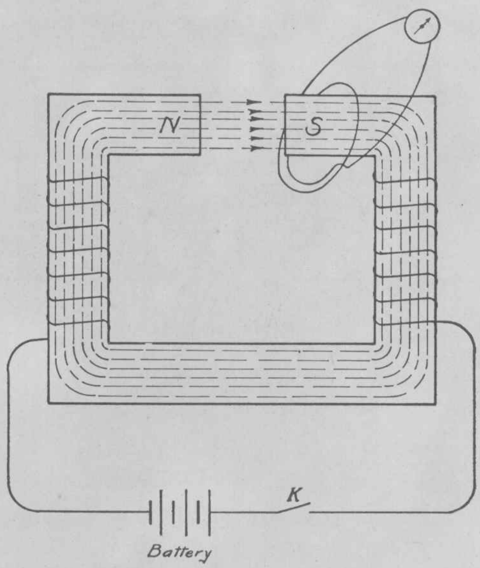

FIG. 6.—A coil linked twice with lines of force of an electromagnet.

circuit links the lines ten times, then the induced voltage would be ten times as great, and so on.

To sum up: The magnitude of an induced voltage in any circuit depends, (1) on the rate at which a change in the number of magnetic lines linking a circuit takes place, and (2) on the number of times the lines are linked with the circuit. It follows, therefore, that if a circuit is linked a large number of times with magnetic lines, and these disappear (or are introduced) very quickly, extremely high voltages may be induced.

Meaning of A.C.—Sinusoidal

6. Suppose a single loop of wire, ABCD, Figure 7, is rotated in the region between two powerful magnetic poles N and S. As the wire AB goes down it cuts across lines of force and in it we have an induced voltage in the direction of the arrow. At the same time the portion of the loop CD goes up, thus cutting the same lines in the opposite direction, and an induced voltage in the opposite direction

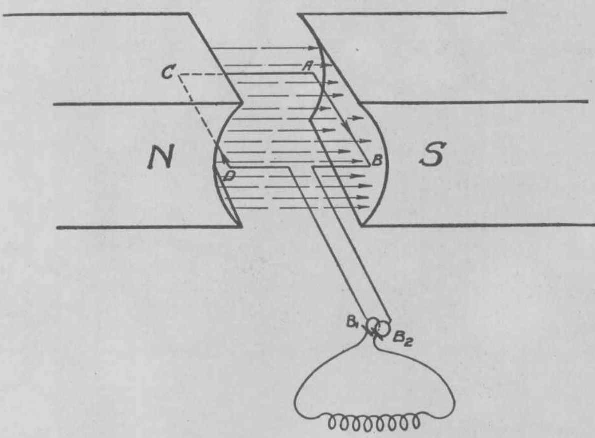

Fig. 7.—A simple arrangement to generate a sinusoidal current.

(Section 4) results. If, now, the ends of the loop are connected to two slip rings upon which rest brushes B_1 and B_2 connected by some external conducting circuit, an induced current may flow. Evidently all the time AB is going down and CD up (that is, for half a revolution) a circuit will flow through this circuit in the direction indicated by the arrows. After AB has reached its lowest position, however, it begins to move up, and then the direction of the induced voltage will change. At the same time, the wire CD will have reversed its direction (up to down) and in it too the induced voltage reverses. It follows, therefore, that during the second half revolution the current throughout the circuit will flow in the opposite direction to that during the first, and that as rotation continues, the current reverses in direction every half revolution.

Not only, however, is there a reversal of current (or, if you like, of polarity between the brushes B_1 and B_2) but the *strength* of the current is continually changing. This will be evident if it is realized that when the wire AB is passing through its highest position and the wire CD through its lowest, each wire is moving parallel to the magnetic lines and hence for a short interval of time there is no cutting and, therefore, no induced voltage and no current. As AB goes down (and CD up) the lines are cut more and more quickly until after one-quarter of a revolution both AB and CD are moving directly at right angles to the lines. At this instant, therefore, the magnetic lines are cut at the fastest rate and the biggest induced voltage results. For the next quarter of a revolution, the lines are cut less and less quickly until AB reaches the bottom (CD the top) and once more, for a brief moment, each wire is moving parallel to the lines, and the voltage has dropped to zero again. Evidently, then, during one complete revolution, the current in the circuit will gradually rise in one direction to a maximum value, drop until it is zero, from which it gradually climbs to a maximum in the opposite direction, again falling to zero. If the loop is rotated at steady speed and in a uniform magnetic field, the manner in which the current changes with time is represented graphically in Figure 8.

A current of this type is an *alternating* one (A.C.) as well as *sinusoidal*. Obviously a sinusoidal current is characterized by (1) changing polarity and (2) gradual "smooth" changes in intensity. In passing it may be noted that by using a mechanical means, such as a revolving drum, to put in and take out resistance gradually from a circuit, sinusoidal effects without changing polarity may be obtained.