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Electron accelerators: History, applications, and perspectives

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HIGHLIGHTS

- We present an outlook on sources of radiation, focusing on electron accelerators.
- We review important advances for the development of modern electron accelerators.
- We outline advances that allowed for brighter synchrotron light sources.
- We describe the history of the development of electron accelerators in Brazil.

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ABSTRACT

This paper will present an outlook on sources of radiation, focusing on electron accelerators. We will review advances that were important for the development of particle accelerators, concentrating on those that led to modern electron accelerators. Electron accelerators are multipurpose machines that deliver beams with energies spanning five orders of magnitude, and are used in applications that range from fundamental studies of particle interactions to cross-linking polymer chains in industrial plants. Each accelerator type presents specific characteristics that make it more suitable for certain applications. Our work will focus on radiation sources for medical applications, dominated by electron linacs (linear accelerators), and those used for research, field where electron rings dominate. We will outline the main technological advances that occurred in the past decades, which made possible the construction of machines fit for clinical environments. Their compactness, efficiency and reliability have been key to their acceptance in clinical applications. This outline will include advances that allowed for the construction of brighter synchrotron light sources, where the relevant beam characteristics are good optical quality and high beam current. The development of insertion devices will also be discussed, as well the development of Free Electron Lasers (FEL). We conclude the review with an outline of the new developments of electron accelerators and the expectations for Energy Recovery Linacs.

1. Introduction

Particle accelerators are usually complex and expensive machines. The effort needed to develop and improve them, both in manpower and in money, has been enormous. This could only have been achieved with a sound scientific motivation, which has been, since the early days, the knowledge of the structure of matter, but has been greatly widened with the discovery of other uses for accelerators.

We can associate the beginning of this journey to Sir Ernest Rutherford, who used alpha particles to probe the atom and completely changed its accepted conception, introducing the nucleus. The need to study ever smaller dimensions could only be satisfied with the use of energetic particles that were not available in natural radioactive sources. In his presidential address to the Royal Society, in 1927 (Rutherford, 1928), Rutherford urged, "I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances". By then, two ideas were already available: Ising's linear accelerator and Wideröe's ray transformer (later to be developed by Kerst and be known as the betatron), but approximately 15 years and a global war went through before they could be implemented. First attempts to produce accelerated particles were based on electrostatic accelerators, the major challenge being the production of high enough voltages. Radioactive sources used by Rutherford in his experiments emitted alpha particles with energies up to 10 MeV. Classical reasoning expected that at least this amount of energy would be needed to reach the nucleus. This was sort of depressing, since this kind of voltage was completely out of reach. Fortunately, with the development of

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quantum mechanics, George Gamow introduced the concept of tunnelling and helped to explain radioactive alpha decay. He then inverted the argument and showed that about 300 keV should be enough to induce a nuclear reaction. That gave impetus to Cockcroft and Walton to build an electrostatic generator to reach this voltage.

2. First attempts: electrostatic accelerators

Rutherford was not the only one urging for particle accelerators. In 1924, Robert van de Graaff, then a young mechanical engineer studying physics at the Sorbonne, attended a lecture by Louis de Broglie in which he hoped for a machine that could be used for controlled studies of the atomic nucleus. This lecture inspired van de Graaff, who, between 1925 and 1929, while at Oxford, developed the concept that is now known as the van de Graaff generator. In Princeton, in 1929, he built a prototype that worked at 80 kV. His idea of accumulating charges in a terminal, mechanically transported from a voltage source by a moving dielectric belt, is unique and still in use. His first device operated at 1.5 MeV was published in 1931 (van de Graaff, 1931), and a 1933 (van de Graaff et al., 1933) paper, which carries "high voltages for nuclear investigations" in the title, deals only with high voltage production. In a 1935 paper, Tuve et al. (1935) report on using a van de Graaff generator to accelerate protons for nuclear physics studies in the Department of Terrestrial Magnetism, Carnegie Institution of Washington. Even though first published in 1932, after van de Graaff's paper, Cockcroft and Walton were the first to report (Cockcroft and Walton, 1932) a nuclear reaction ($^{7}\mathrm{Li}+p\rightarrow{}^{8}\mathrm{Be}\rightarrow\alpha+\alpha$) produced by particles accelerated by a human-made device. Cockcroft and Walton developed a 600-kV voltage-multiplying column, which was connected to an accelerating column used to accelerate the protons.

3. First circulating accelerators: the "ray transformer" and the cyclotron

Electrostatic accelerators were successful and are still used today in several applications, but they have limitations, very high voltages being a technical nightmare. As early as 1924 a Swedish physicist, Gustav Ising, proposed the theoretical concept of a linear accelerator, a device that could accelerate particles to the equivalent of a very high voltage by the accumulation of a series of steps of moderate voltage. By 1922 an important character appears in this history: Rolf Wideröe, then a young Norwegian PhD student in Karlsruhe. Wideröe's importance is threefold: he created the concept (in detail) of what he called the "ray transformer", which was latter applied by Donald Kerst to develop the betatron. He built the first linear accelerator, based on Ising's work. The lack of a high frequency power supply made this first linac attempt just a "proof of principle", since it accelerated potassium ions to just 50 keV or so. Nevertheless, this work, in the hands and in the mind of Ernest O. Lawrence, gave birth to the cyclotron, a very successful type of accelerator. And finally, just to show how innovative Wideröe was: as early as 1943 he conceived the idea (and got a patent for it) of colliding particle beams instead of bombarding stationary targets (Voss, 1997), an idea that took 18 years to become real, when the AdA electron–positron collider started operation in Frascatti, Italy. Several other colliders (electro–electron, proton–proton, electron–positron, ion–ion) followed, and are the leading tools in the study of the Standard Model and its limits.

Our focus is on electron accelerators, so we will leave cyclotrons apart, since they are not suited for accelerating electrons because these become relativistic very quickly and loose synchronicity with the accelerating field. But betatrons are very important in this history, since their development set the foundations for the development of other circulating accelerators like synchrotrons and microtrons.

In his 1928 paper which inspired Lawrence to build the cyclotron, Wideröe also reported his ideas on the "ray transformer" that can be understood as the betatron principles: acceleration of the electrons by the electric field induced by a time varying (increasing) magnetic field; and the electrons are kept in a circular orbit by a bending magnetic field, which he calculated should be one half the average induction magnetic field. Unfortunately, Wideröe was discouraged by his supervisor to pursue the "ray transformer" idea, but decided to build the linac, following Isings ideas.

The betatron, though having no accelerating cavities, was the first circular machine to have a rising field that had to keep up with the rising energy of the accelerated electrons. To keep the electrons on the desired circular orbit designers had to understand their modes of oscillation, both sideways and vertically, around the circular path they were supposed to follow. Those "betatron oscillations," as they are still known, are very important in understanding the basic behaviour of the beam in much larger circular machines, like synchrotrons and storage rings.

There were several failed attempts to build a circular induction machine between 1925 and 1938: the reasons for failure are several, from lack of focusing to the beginning of WWII, but some understanding of the problem was built. In 1939, at the University of Illinois, Donald Kerst and Robert Serber extended a previous theoretical work by Walton on the motion of electrons under spatially and time-varying fields. This work, published in 1941 (Kerst and Serber, 1941) not only led to the first operating betatron (Kerst, 1940) but also served as a solid basis for the analysis of particle motion in all future circular accelerators. The first betatron had a 7.5-cm radius tube that produced 2.3 MeV electrons, generating X-rays equivalent to a tenth of a Ci of radium, later improved to the equivalent of a few Ci. This comparison is interesting to show the focus of electron accelerators at the time, to produce X-rays for medical and nondestructive testing applications. After this initial achievement, Kerst took a year leave from the University and joined General Electric Labs, where he built two betatrons, of 20 and 100 MeV. During WWII he built a 4 MeV portable betatron for inspection of unexploded bombs in the fields. After the war, Kerst, back at the University of Illinois, built an 80-MeV machine, and then, around 1950, the largest betatron ever built, for 300 MeV.

Betatrons were short-lived, for the development of radio and radar technology during the war allowed for the construction of electron synchrotrons that were cheaper and more efficient for the acceleration of high-energy electrons.

4. Phase stability and RF Acceleration

After circumventing the problems associated with high voltages by the introduction of cyclotrons and betatrons, accelerator physicists faced other limiting issues. Betatrons and cyclotrons presented a severe energy limitation: since magnetic fields were limited to about 2 T, energy increase meant a corresponding increase in orbit radius, which demanded increasing the size of the magnet, and gradually sizes and prices were becoming prohibitive. Other energy limitations were, for cyclotrons, the relativistic mass increase that detuned protons out of synchronicity above around 30 MeV; for betatrons, energy loss due to radiation emitted by the orbiting electrons.