50 YEARS OF SR

J. Synchrotron Rad. (1998). **5**, 135–139

Synchrotron Radiation – Early History

John P. Blewett†

Brookhaven National Laboratory, Upton, NY 11973–5000, USA

(*Received 4 August 1997; accepted 21 October 1997*)

The scientific history of the work that led to the prediction and observation of synchrotron radiation goes back more than a century. This paper is a summary of that history.

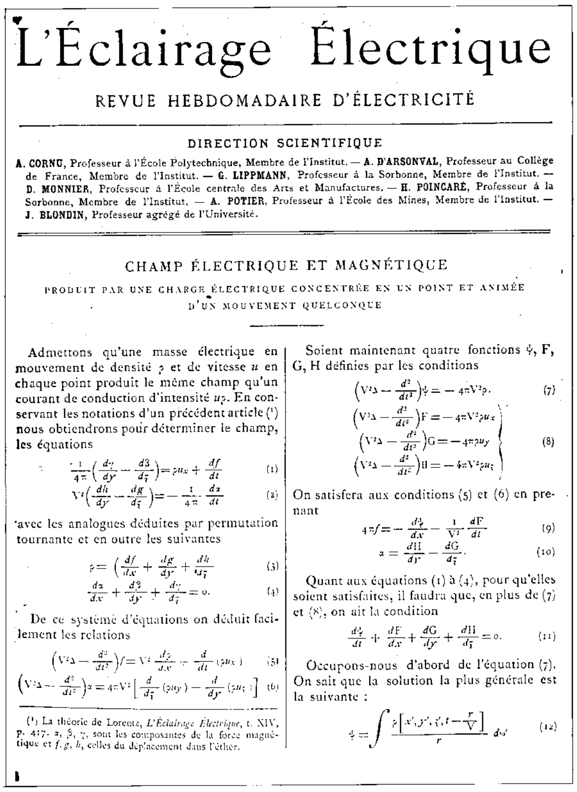
Keywords: history of synchrotron radiation; Liénard; Thomson; Schott; General Electric Research Laboratory; Schwinger.

This year is the 50th anniversary of the first visual observation of synchrotron radiation and the 52nd of its first indirect observation. To the younger generation of physicists, 1945 must seem to be the beginning of synchrotron radiation's history – it was detected then, and visually observed in 1947, both historic events occurring in the Research Laboratory of the General Electric Company. When I first observed the effects of synchrotron radiation in 1945 I was not aware of the fact that the radiation from accelerated electrons had been predicted and analyzed before 1908. Since then I have acquired a healthy respect for the pioneers who were the first to study the radiation from charged particles. Their predictions were correct – but they had to wait for the acceleration of electrons to multi-MeV energies for the predicted radiation to become detectable and visible.

The theoretical understanding began, of course, in 1873 with Maxwell, who made it evident that changing charge densities and electric currents would result in electromagnetic fields that would radiate outward, headed for infinity. In 1887, Heinrich Hertz, a student of Helmholz, demonstrated such waves for his professor – and thus were laid the foundations for the theory of synchrotron radiation.

The general theory of radiation from changing currents and accelerated charges proved to be extremely complicated, not so much conceptually as algebraically – equations began to cover whole pages. The first major step forward, so far as we are concerned, was made in 1898 when Alfred Liénard, a professor at the still prestigious École des Mines in Paris, applied the concept of what are now called 'retarded potentials'. This is simply the procedure that, when we calculate field patterns here from moving charges over there, we insert into our equations the positions and motions of the charges at the time when the radiation started to travel from there to here. This can result in a major simplification of the analysis.

Liénard's paper was published in *L'Éclairage Électrique* ('Electric Lighting') (Liénard, 1898). Fig. 1 shows the first page of this paper, which I found in a somewhat dilapidated condition in the Engineering Societies Library in New York. It was a weekly journal on developments in electricity and was guided, as you can see, by a very distinguished board of editors. The paper was entitled 'Electric and Magnetic Field Produced by an Electric



L'Éclairage Électrique

REVUE HEBDOMADAIRE D'ÉLECTRICITÉ

DIRECTION SCIENTIFIQUE

A. CORNU, Professeur à l'École Polytechnique, Membre de l'Institut. — **A. D'ARSONVAL**, Professeur au Collège de France, Membre de l'Institut. — **G. LIPPMANN**, Professeur à la Sorbonne, Membre de l'Institut. — **D. MONNIER**, Professeur à l'École centrale des Arts et Manufactures. — **H. POINCARÉ**, Professeur à la Sorbonne, Membre de l'Institut. — **A. POTIER**, Professeur à l'École des Mines, Membre de l'Institut. — **J. BLONDIN**, Professeur agrégé de l'Université.

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

PRODUIT PAR UNE CHARGE ÉLECTRIQUE CONCENTRÉE EN UN POINT ET ANIMÉE D'UN MOUVEMENT QUELCONQUE

Admettons qu'une masse électrique en mouvement de densité ρ et de vitesse u en chaque point produit le même champ qu'un courant de conduction d'intensité $u\rho$. En conservant les notations d'un précédent article (¹) nous obtiendrons pour déterminer le champ, les équations

$$-\frac{1}{4\pi}\left(\frac{d\gamma}{dy}-\frac{d\beta}{dz}\right)=\rho u_x+\frac{df}{dt} \qquad (1)$$

$$V^2\left(\frac{dh}{dy}-\frac{dg}{dz}\right)=-\frac{1}{4\pi}\frac{d\alpha}{dt} \qquad (2)$$

avec les analogues déduites par permutation tournante et en outre les suivantes

$$\rho=\left(\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}\right. \qquad (3)$$

$$\frac{d\alpha}{dx}+\frac{d\beta}{dy}+\frac{d\gamma}{dz}=0. \qquad (4)$$

De ce système d'équations on déduit facilement les relations

$$\left(V^2\Delta-\frac{d^2}{dt^2}\right)f=V^2\frac{d\rho}{dx}+\frac{d}{dt}(\rho u_x) \qquad (5)$$

$$\left(V^2\Delta-\frac{d^2}{dt^2}\right)\alpha=4\pi V^2\left[\frac{d}{dz}(\rho u_y)-\frac{d}{dy}(\rho u_z)\right] \qquad (6)$$

Soient maintenant quatre fonctions ψ, F, G, H définies par les conditions

$$\left(V^2\Delta-\frac{d^2}{dt^2}\right)\psi=-4\pi V^2\rho. \qquad (7)$$

$$\left.\begin{aligned}\left(V^2\Delta-\frac{d^2}{dt^2}\right)F&=-4\pi V^2\rho u_x\\ \left(V^2\Delta-\frac{d^2}{dt^2}\right)G&=-4\pi\rho u_y\\ \left(V^2\Delta-\frac{d^2}{dt^2}\right)H&=-4\pi V^2\rho u_z\end{aligned}\right\} \qquad (8)$$

On satisfera aux conditions (5) et (6) en prenant

$$4\pi f=-\frac{d\psi}{dx}-\frac{1}{V^2}\frac{dF}{dt} \qquad (9)$$

$$\alpha=\frac{dH}{dy}-\frac{dG}{dz}. \qquad (10)$$

Quant aux équations (1) à (4), pour qu'elles soient satisfaites, il faudra que, en plus de (7) et (8), on ait la condition

$$\frac{d\psi}{dt}+\frac{dF}{dx}+\frac{dG}{dy}+\frac{dH}{dz}=0. \qquad (11)$$

Occupons-nous d'abord de l'équation (7). On sait que la solution la plus générale est la suivante :

$$\psi=\int\frac{\rho\left[x',y',z',t-\frac{r}{V}\right]}{r}\,d\omega' \qquad (12)$$

(¹) La théorie de Lorentz, *L'Éclairage Électrique*, t. XIV, p. 417. α, β, γ, sont les composantes de la force magnétique et f, g, h, celles du déplacement dans l'éther.

1

Figure 1
First page of Liénard's paper.

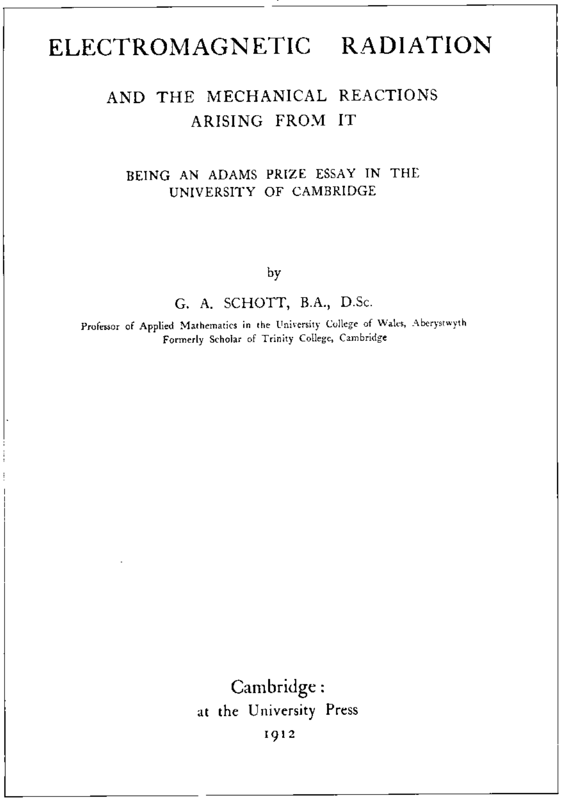
---

† Retired.

Journal of Synchrotron Radiation
ISSN 0909-0495 © 1998

Charge Concentrated at a Point and Traveling on an Arbitrary Path'. In this historic paper Liénard worked out the basic theory of synchrotron radiation. Here is the formula for the rate of loss of energy by an electron traveling on a circular path just as it now appears in modern papers on synchrotron radiation. Fortunately, the equations of electromagnetic theory are invariant under transformations between moving systems. To calculate the characteristics of synchrotron radiation you do not need relativity theory – which was fortunate for Liénard because relativity had not yet been invented in 1898.

Between 1890 and 1910 a lot happened. In particular there had been much speculation since the discovery in 1858 of the 'cathode rays' that emerged through holes in the anodes of electric discharge tubes. The British, mainly guided by J. J. Thomson, believed that they were particles. The Germans and others on the continent, except for Helmholz, thought that they were waves. Then, in 1883, Hertz showed that their paths could be bent when a magnet was held nearby, but he could not feel any effect on the magnet. Apparently an electric field had no effect on the rays. In the following year, J. J. Thomson, newly established as head of the Cavendish Laboratory at Cambridge, took charge of the situation. He showed that, in a sufficiently good vacuum, an electric field did deflect the rays. With a rotating mirror he measured the rate of propagation of luminosity from the cathode in a discharge tube. This he took to be a measure of the velocity of the rays; it proved to be only a small fraction of the velocity of light. Finally, in 1897, with a combination of electric and magnetic fields, he measured *e*/*m*, the ratio of charge to mass of the particles. Assuming that the charge was the lowest associated with the atom through experiments on electrolysis, he concluded that the mass of the particle was only about 1/2000th of that of the H atom. Finally he showed that the particles emitted when light falls on metal surfaces had the same *e*/*m* as the cathode rays. In short, he discovered the electron.


ELECTROMAGNETIC RADIATION

AND THE MECHANICAL REACTIONS
ARISING FROM IT

BEING AN ADAMS PRIZE ESSAY IN THE
UNIVERSITY OF CAMBRIDGE

by

G. A. SCHOTT, B.A., D.Sc.
Professor of Applied Mathematics in the University College of Wales, Aberystwyth
Formerly Scholar of Trinity College, Cambridge

Cambridge:
at the University Press
1912

Figure 2
Title page of George Schott's Adams Prize Essay which covered the theory of synchrotron radiation.

I was born in 1910 just after all of this activity. I learned physics in Toronto from Sir John McLennan, a good friend of Lord Rutherford, then the Director of the Cavendish Laboratory. I finally made it to the Cavendish for a year in 1936, through to 1937, and there was J. J. Thomson, retired since 1919 but still coming frequently to the Laboratory on his bicycle.

I now return to the subject at hand. You can see how timely was Liénard's work, appearing in 1898, the year after the discovery of the electron. The charge assumed in his calculations was no longer merely hypothetical and analysis of its radiation fields was clearly relevant, though it was not clear exactly how, to the emission of light and other radiation.

Liénard's work was supplemented by another, I believe independent, approach to the retarded potential idea by Emil Wiechert, Professor of Geophysics at the University of Göttingen, who published in the *Archives Neerlandaises* in 1900 (Wiechert, 1900). Wiechert was interested in all kinds of waves, particularly seismic waves from earthquakes. In any case, Wiechert's work had the result that textbooks often refer to the 'Liénard–Wiechert potentials' – all this in spite of the fact that the concept had been proposed in 1867 by Ludwig Lorenz, in Copenhagen. Lorenz had been a leader in inventing electromagnetic theory but Maxwell was too far ahead.

The really major event on the theoretical front occurred in 1908 when George A. Schott – Scholar of Trinity College, Cambridge – won the Adams Prize with his essay, 'Electromagnetic Radiation' (Schott, 1912). The essay was published in 1912, by which time Schott had become Professor of Applied Mathematics in the University College of Wales in Aberystwyth. Fig. 2 shows the title page of this splendid opus.

The Adams Prize was a substantial one awarded by Cambridge University for a mathematical essay on a topic chosen by the examiners. It was evidently a prestigious affair won by monumental essays on topics of contemporary interest. It had been won in 1859 by Clerk Maxwell for an essay 'On the Stability of Saturn's Rings'. It was then won in 1883 by J. J. Thomson for an essay entitled 'Vortex Rings' describing some ideas then considered plausible on the structure of the atom. In 1900 it was won by Joseph Larmor whose essay was called 'Aether and Matter' and discussed the problems associated with the 'luminiferous aether' which our forbears felt was essential for the transmission of light from here to there, particularly through regions of total vacuum.

Schott's essay is the only one of those mentioned that maintains its interest to the present day. His carefully evolved ideas, for the most part, are as valid as when they were written. The reasons for this emerge partially from the introduction to the essay from which I extract the following quotations:

(Please try to imagine yourselves back in 1908 – remember that the atom did not yet have a nucleus.)

> In consequence of the discoveries of the last few years . . . . . a great need has arisen for a comprehensive Electron Theory of Matter. . . . A beginning has been made by J. J. Thomson in his well known paper on the Structure of the Atom and in his books . . . . but these investigations have been carried out under the restriction . . . . that the negative electrons in the atomic model move with velocities so small that they can be treated like the particles of ordinary mechanics. Moving electric charges, however, do not behave like particles of ordinary mechanics; they do not obey the Law of Action and Reaction, their mass varies with their speed, and they generate a magnetic field which reacts on their motion in various ways . . . .
>
> Moreover it is by no means certain that all the electrons inside the atom are moving with speeds small compared with that of light; we know that beta particles are expelled from comparatively stable atoms like that of radium with speeds differing from that of light by only two percent . . . .
>
> For these reasons it is desirable . . . . to develop the theory of moving electric charges with as few restrictions as possible. I have refrained from making any use either of the Postulate of Relativity, or of the Aether Hypothesis which, by some, are regarded as inconsistent with each other.

Schott's essay is 327 pages long and is bound in the blue covers which were familiar to us students of the early twentieth century, binding Cambridge texts such as Jeans' *Electricity and Magnetism* and Fowler's *Statistical Mechanics*. Schott states the basic theoretical concepts, then applies them to all sorts of motions of single electrons or of a variety of groups of electrons. The case of radiation from an electron travelling in a circular orbit is one of many examples. All electron velocities are considered, including velocities greater than that of light.

Schott's derivation of the characteristics of what we now call 'synchrotron radiation' includes first the energy loss – here he verifies Liénard's conclusion that energy loss increases as the fourth power of electron energy (he was familiar with Liénard's work and makes frequent references to Liénard). Then he derives the angular distribution and the state of polarization of the radiation. Finally, he studies the frequency distribution of the radiation and derives an expression describing the radiation spectrum. But his equation involves Bessel functions of very high order, not to be found in available tables. Schott gives an alternate form but it was equally intractable. He did not pursue the character of the radiation spectrum further although the actual spectrum of synchrotron radiation is described by his equation.

Schott said what was to be the last word for three decades.

Interest in the radiation from accelerated electrons appears first to have reemerged in the Soviet Union. I. Pomeranchuk of the Physical Institute of the State University in Leningrad became concerned in 1939 about cosmic-ray electrons entering the earth's magnetic field and losing energy by emitting what we now call 'synchrotron radiation.' He concluded (Pomeranchuk, 1940) that this effect would be important only for electrons with primary energies greater than 10^{16} eV.

An electron accelerator, later to be called the betatron, had been invented in 1922 and appeared capable of acceleration to very high energies. It was reinvented in 1928 by Rolf Wideröe of Norway; he built models but was unable to make them work. Then, in 1939–1940, Don Kerst and Bob Serber of the University of Illinois showed what was necessary in magnetic field shaping to prevent the accelerated beam from blowing up. Kerst built a 2.3 MeV model which worked immediately as predicted; he published a paper describing it in 1941 (Kerst, 1941). This excited the interest of the General Electric Company who saw it as an interesting source of X-rays. Kerst was induced to visit the GE Research Laboratory where he would build a 20 MeV betatron. He was assisted by W. F. Westendorp, one of GE's finest engineers. The machine was completed and operated in 1941 and was described in a paper in the *Review of Scientific Instruments* in 1942 (Kerst, 1942).

Kerst and Serber were aware of Schott's work and of the radiation to be expected from accelerated electrons. They concluded, however, that at 20 MeV the effects of the radiation would be negligible, so in their papers they made no mention of radiation or of the problems it would introduce at higher energies.

Kerst returned to the University of Illinois, taking the 20 MeV betatron with him and leaving W. D. Coolidge, Director of the GE Research Laboratory, deeply inter-

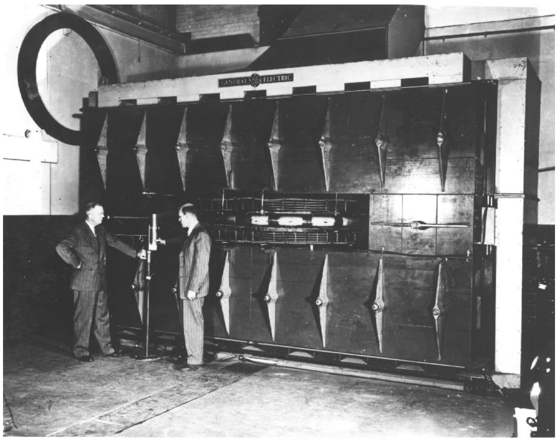


Figure 3
The 100 MeV betatron at the General Electric Research Laboratory with E. Charlton (left) and W. Westendorp.

ested in the new X-ray source. Also interested were E. E. Charlton and Westendorp, who decided to build a record-breaking machine for 100 MeV. This they proceeded to do with typical professional skill. The final product (Westendorp & Charlton, 1945) was a splendid object weighing 130 tons; it emitted 2600 r of X-rays per minute and a deafening noise when operated at 60 cycles per second. Fig. 3 shows the machine with Charlton at the left and Westendorp pointing to the vacuum chamber.

In the meantime the war was over and the Russians returned to thinking about accelerators and their problems. Pomeranchuk, with D. Ivanenko, published another paper in 1944 (Ivanenko & Pomeranchuk, 1944*a*) about radiation losses in higher energy betatrons. Possibly, they thought Americans might not subscribe to the *Akademia Nauk Doklady* – as was indeed the case in those days – so they wrote a short letter to the *Physical Review* (Ivanenko & Pomeranchuk, 1944*b*) including only the energy-loss formula with some remarks about its significance for high-energy betatrons.

I was a member in those days of Albert Hull's group in the GE Research Laboratory. My specialty was thermionic emission and I knew very little about accelerators. But Hull noticed the Russian letter in the *Physical Review* and asked me what I thought of it. All innocent of past history, I went back to fundamentals, redid Liénard and Schott and concluded that the Russians were right. Moreover, it seemed to me that the energy losses due to radiation should be detectable in our 100 MeV betatron. The energy loss would be only about 10 eV per revolution. But, at the rates of acceleration used, the final energy would be reduced from 100 MeV to about 99 MeV. I was not universally believed – Westendorp argued that the ring of electrons being accelerated constituted a d.c. current and everybody knows that d.c. currents do not radiate. But I calculated a predicted orbit shrinkage; we measured it, and it agreed with my prediction. I did some further analysis, again duplicating Liénard and Schott, and concluded that the radiation was emitted in a narrow cone in the forward direction and hence that it should appear as a great many harmonics of the circulation frequency of about 50 MHz. With a detector we looked over the range up to 1000 MHz but we found nothing. Then I became aware that Julian Schwinger was working on the same problem and had demonstrated that the harmonic range went much higher than I had guessed, indeed extending into the range of visible wavelengths. Unfortunately the betatron's vacuum chamber was opaque so the visible radiation was not visible to us. I published my conclusions in the *Physical Review* in 1946 (Blewett, 1946). Schwinger gave a paper at an APS meeting in the same year but did not publish his conclusions until 1949. More about that paper later.

The future of the betatron was blasted in 1945 when the synchrotron was invented by McMillan and Veksler. We, at GE, were excited and enthused. We evolved a method for synchrotron injection using betatron acceleration and, piously claiming only to try to contribute to the accelerator art, we hastily threw together some old betatron parts to make a 70 MeV synchrotron (Pollock *et al.*, 1947). Secretly we hoped to be in operation before McMillan could finish his proposed 300 MeV machine and so be the first in the world to bring a synchrotron into operation. In this unworthy motive we were frustrated, however, by the British Admiralty team of Goward and Barnes who very quickly put together a little 8 MeV synchrotron and so carried off the laurel wreath.

I left to join the new Brookhaven National Laboratory shortly after we, at GE, started construction of the 70 MeV machine. In charge of construction was my old friend Herb Pollock; he was ably assisted by Robert Langmuir, Frank Elder and Anatole Gurewitsch. Our machine became the world's second operating synchrotron in 1947.

On 24 April 1947 the machine was in operation and some components were being pushed to rather high operating levels. Some sparking had occurred and a large mirror had been set up at the end of the shielding wall whose function was protection of the control area from the synchrotron's intense output of X-rays. With this mirror it was possible to view the vacuum chamber which was transparent, not opaque like the one in the betatron. Floyd Haber, a machinist working with the synchrotron team, was detailed to watch the mirror. He signaled immediately to turn the machine off because he saw an arc. More careful observation made it clear to Pollock and Langmuir, who were operating the machine, that this was indeed my predicted radiation (Elder *et al.*, 1947). A small very bright bluish-white spot appeared at the side of the chamber where the beam was approaching the observer. At lower energies the spot changed color. At 40 MeV it was yellow and at 30 MeV it was red and very faint; at 20 MeV it was no longer visible. Fig. 4 shows the synchrotron with the light spot very much in evidence, and Fig. 5 is a picture of the GE team looking at the vacuum chamber of the 70 MeV machine. From left to right they are Bob Langmuir, Frank Elder, Toly Gurewitsch, Ernest Charlton and Herb Pollock.

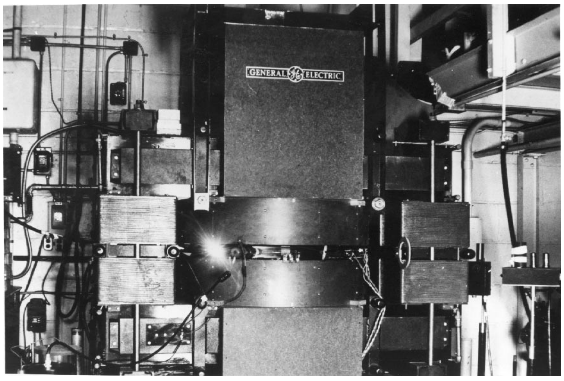


Figure 4
The 70 MeV General Electric synchrotron in 1947 with clearly visible synchrotron light spot (light splash in the lower left center of the picture).

Figure 5
The General Electric team (from left to right, Langmuir, Elder, Gurewitsch, Charlton and Pollock) looking at the vacuum chamber of the 70 MeV synchrotron – the world's second synchrotron.

The visible beam of 'synchrotron radiation', as it was now called, was an immediate sensation. Charles E. Wilson, president of GE, brought the whole Board of Directors to see it. During the next two years there were visits from six Nobel Prize winners. Another visitor, who showed very little interest, was Ronald Reagan who, at that time, was doing publicity for the General Electric Company.

It remains only to discuss two important theoretical papers. The first was a final definitive word from the Soviet Union. This paper 'The Radiation of Fast Electrons in the Magnetic Field' by Arzimovich and Pomeranchuk appeared in the USSR *Journal of Physics* in 1945 (Arzimovich & Pomeranchuk, 1945). The references quoted in this paper are interesting. They include two previous papers by Pomeranchuk, an early paper on the betatron by Kerst, and Heitler's 1936 book, *The Quantum Theory of Radiation*. Apparently the authors were as innocent as I was of acquaintance with the earlier work. In their paper, Arzimovich and Pomeranchuk start from scratch and derive the energy loss and angular distribution of the radiation. They tackle the problem of the spectrum of the emitted radiation and establish its general character – for example, it will peak at a wavelength inversely proportional to the cube of the electron energy. But they do not establish the radiation spectrum in detail.

Incidentally, Heitler's book, which I have in the second, 1944 edition, gives the classical derivation for the radiation from an accelerated electron. Heitler uses what he calls 'Wiechert potentials' and makes no mention of either Liénard or Schott.

The most quoted theoretical paper on synchrotron radiation 'On the Classical Radiation of Accelerated Electrons' (Schwinger, 1949) was published, as I mentioned earlier, by Schwinger in 1949. This paper is an elegant presentation of the properties of radiation from electrons travelling on arbitrary paths. This is a definitive work and is presented with such mathematical skill that it has diverted attention from its many worthy predecessors, whose work I have been discussing. Schwinger derives the total energy loss, angular distribution and polarization of the radiation, all properties previously derived by several authors. When it comes to the spectral distribution, using the same procedures as did Schott, and indeed giving credit to Schott, he derives the same intractable expression in Bessel functions of high order. Here, however, he makes a major contribution. He recognizes the relation between the derivation used and that involved with the Airy integrals and reduces the formulae to forms using tabulated functions. This important contribution has made it possible for designers of synchrotron radiation sources to predict with precision exactly what will be the characteristics of the radiation that will be available.

So much for ancient history. What has happened since 1947 you will learn from the papers that follow. In conclusion, I emphasize that, in those days, synchrotron radiation was important only because it made trouble for designers of high-energy electron synchrotrons. It was of some use to accelerator builders in helping to indicate machine performance. But it was not until 1965 that the Solid State Panel of the National Academy of Sciences set up a committee to evaluate the possible utility of synchrotron radiation.

When I see at present the thousands of users at facilities like Brookhaven's NSLS, Argonne's APS, Berkeley's ALS, and the dozens of other synchrotron radiation facilities, I am constrained to conclude with the proverb 'When Fate deals you nothing but lemons, make lemonade.'

References

Arzimovich, L. & Pomeranchuk, I. (1945). *J. Phys. IX*, p. 267.

Blewett, J. P. (1946). *Phys. Rev.* **69**, 87–95.

Elder, F. R., Gurewitsch, A. M., Langmuir, R. V. & Pollock, H. C. (1947). *Phys. Rev.* **71**, 829–830.

Ivanenko, D. & Pomeranchuk, I. (1944*a*). *Akad. Nauk. Dokl.* **44**, 315.

Ivanenko, D. & Pomeranchuk, I. (1944*b*). *Phys. Rev.* **65**, 343.

Kerst, D. W. (1941). *Phys. Rev.* **60**, 47–53.

Kerst, D. W. (1942). *Rev. Sci. Instrum.* **13**, 387–394.

Liénard, A. (1898). *L'Éclairage Élec.* **16**, 5.

Pollock, H. C., Langmuir, R. V., Elder, F. R., Blewett, J. P., Gurewitsch, A. M. & Watters, R. L. (1947). *Phys. Rev.* **70**, 798.

Pomeranchuk, I. (1940). *J. Phys. II*, p. 65.

Schott, G. A. (1912). *Electromagnetic Radiation.* Cambridge University Press.

Schwinger, J. (1949). *Phys. Rev.* **75**, 1912–1925.

Westendorp, W. F. & Charlton, E. E. (1945). *J. Appl. Phys.* **16**, 581–593.

Wiechert, E. (1900). *Arch. Neerl.* pp. 549–573.