The World of Synchrotrons

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A summary of results on synchrotron radiation is presented along with notes on its properties and applications. Quantum aspects are briefly mentioned. Synchrotron radiation facilities are described briefly with a detailed coverage of the accelerator programmes in India.

Introduction to Synchrotron Radiation

Charged-particles when accelerated radiate electromagnetic energy. This interesting physical phenomenon, now known by the name *synchrotron radiation* had its theoretical beginnings, a long time ago, at the time of classical electrodynamics. These theoretical studies had to wait for about half a century till the development of charged-particle accelerator technology for a direct observation and experimental verification. It was experimentally observed for the first time in 1947 in the 70 MeV electron synchrotron and hence the name *synchrotron radiation*. This observation generated a renewed interest in synchrotron theory. Synchrotron radiation was an irritant in early electron synchrotrons and storage rings. But it was soon realized that synchrotron radiation was a very valuable product in itself for research applications requiring intense and bright sources of light over a wide range of wavelengths. Electrons lose a large amount of energy in the form of synchrotron radiation putting a limit on the maximum attainable energy in a given type of accelerator. Let us first consider the case of the betatron. The betatron is a cyclic electron accelerator with a circular orbit of approximately constant radius which provides acceleration through *magnetic induction*. As the beam energy rises synchrotron radiation loses rise and begins to compete with the en-

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ergy gained due to magnetic induction. In practice, the synchrotron radiation begins to become important at about 100 MeV and limits beam energies to about 300 MeV. This challenge of the synchrotron radiation stimulated the development of accelerator technology and further increased the energy of the accelerated particles.

Here, it would be relevant and interesting to mention the particular case of the charged-particles under uniform acceleration, i.e., a constant force. This constant force can be produced, for example, by a constant uniform electrostatic field. From the special theory of relativity we know that a particle under a constant force executes hyperbolic motion. Does a charged-particle under uniform acceleration (hyperbolic motion) radiate? The answer to this question is not yet completely resolved! This topic is listed as one of the several *surprises in theoretical physics* by Peierls [1].

One of the characteristics of the synchrotron radiation is its intensity (energy emitted per unit time). Let us first consider the motion of a charged-particle of rest mass m_0 and charge q in a uniform magnetic field of strength B with the simplification that there is no component of the velocity along the field direction. We further decide to neglect the changes in the trajectory due to the radiation losses. In such a configuration the particle moves in a circle. The radius R of this circle is given by equating centrifugal force with the force $(qB\nu\gamma)$ on the particle,

$$R = \beta\gamma \frac{m_0 c}{qB} = \frac{\beta}{c}\frac{E}{qB}, \tag{1}$$

where the total energy $E = \gamma m_0 c^2$, c is the velocity of light, $\beta = v/c$ and the relativistic factor $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. In 1898 Liénard derived the expression for the total radiation intensity P for a charged-particle moving in circular motion.

$$P = \frac{2}{3}\frac{q^2 c}{4\pi\epsilon_0 R^2}\beta^4\left(\frac{E}{m_0 c^2}\right)^4 \quad (2)$$

The radiated power depends on the rest mass of the radiating particle like $1/m_0^4$. For protons and electrons of the same total energy E the ratio of the radiated powers is

$$\frac{P_p}{P_e} = \left(\frac{m_e}{m_p}\right)^4 = 8.80 \times 10^{-14} \quad (3)$$

Synchrotron radiation is the dominant factor in the design of high energy electron synchrotrons and is an obstacle to exceeding 100 GeV or so in this type of accelerator. Only now synchrotron radiation is becoming a design consideration for proton synchrotrons. In the proton case, single-particle motion, to a very good approximation, exemplifies a Hamiltonian system. Particle motion in electron synchrotrons, on the other hand, is inherently dissipative.

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Quantum Effects in Synchrotron Radiation

Synchrotron radiation was experimentally observed in a period when there was a very keen interest in analyzing the quantum corrections to the prescriptions based on the classical theories. The need of such studies also arose from the desire to achieve higher beam energies with the evolving accelerator technology. A quantum mechanical expression for the radiation intensity was derived by Schwinger which is

$$P^{\text{Quantum}} = P^{\text{Classical}}\left(1 - \frac{55}{8\sqrt{3}}\frac{\epsilon}{E} + \quad\right) \quad (4)$$

where the critical energy of the radiated photon $\epsilon = \hbar\omega_c = \frac{3}{2}\gamma^3\frac{\hbar c}{R}$. For an electron the quantum contributions become effective only at about 10^4 GeV. There have been also studies to assess the effect of spin and

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the anomalous magnetic moment on the radiation intensity. These effects are also noticeable only at very high energies. As far as the radiation intensity is concerned the quantum contributions are of no consequence in any realizable accelerator. However, there are several other ways by which quantum effects manifest at energies realizable in many of the accelerators. The *quantum radiation fluctuations* start having an appreciable effect on the motion of the particles at energies exceeding $E_c = m_0c^2 \left(\frac{m_0cR}{\hbar}\right)^{1/5}$ which for an electron is about 500 MeV. Quantum fluctuations of the radiation have to be taken into account in the engineering calculations of the particle motion. In passing it is to be noted that the quantum corrections to the *beam optics* are related to the powers of the de Broglie wavelength of the charged particle. Hence the quantum corrections to the beam optics are more noticeable at lower energies. One practical application of the *quantum formalism of charged-particle beam optics* would be to get a deeper understanding of the polarized beams.

It has been confirmed that the synchrotron radiation is responsible for the directional orientation of the particle spin *i.e.*, it leads to *radiation self-polarization* of the beam. As a result of the quantum fluctuations of the synchrotron radiation, the particle spin achieves a state whose orientation direction is opposite to that of the magnetic field. The particle beam becomes 92% polarized in about a few hours in many accelerators.

Hence it is possible to observe (and utilize) radiation self-polarization in numerous storage rings. The radiation self-polarization is currently the only method of obtaining relativistic beams with an oriented spin.

Some of the many important properties of the synchrotron radiation are summarized below:

1. The angular distribution of the synchrotron radi-

ation is very sharply peaked in the direction of the particle's velocity vector within an angular width of $1/\gamma$. The radiation is plane-polarized on the plane of the particle's orbit, and elliptically-polarized outside this plane.

2. The radiation spans a continuous spectrum. The power spectrum produced by a high energy particle extends to a critical frequency $\omega_c = \frac{3}{2}\gamma^3\omega_R$, where the cyclotron frequency $\omega_R = \frac{c}{R} = \frac{qB}{\gamma m_0}$.

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These results imply that the synchrotron radiation is extremely intense over a broad range of wavelengths from the infrared through the visible and ultraviolet range and into the vacuum ultraviolet and soft and hard X-ray. The high intensity over a very broad spectrum range and certain other properties (including, collimation, polarization, pulsed-time structure, partial coherence, high-vacuum environment, etc.) make synchrotron radiation a very powerful tool for a variety of applications in basic and applied research and technology. It is particularly important in those parts of the electromagnetic spectrum where laser sources are (presently) not available such as the vacuum ultraviolet, soft and hard X-rays, parts of the infrared, etc. The applications of the synchrotron light span a wide range of domains in fundamental science, applied research and industrial technology.

Numerical Estimates

Using (2) let us estimate the energy radiated by a single particle in one revolution. The time, T of one revolution is $2\pi R/\beta c$ and the energy $\mathcal{E}$ lost is

$$\begin{aligned} \mathcal{E} &= P \times T \\ &= \frac{1}{3}\frac{q^2}{\epsilon_0 R}\beta^3\gamma^4 \end{aligned} \qquad (5)$$

The maximum energy a particle can lose by radiation is all its kinetic energy, $K = (\gamma - 1)m_0c^2$. This can happen

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only at ultrarelativistic energies ($\gamma \gg 1$ and $\beta \approx 1$). The required γ is found by equating $\mathcal{E}$ to K Then one gets

$$\gamma = \frac{1}{\beta}\left[3m_0c^2\frac{\epsilon_0 R}{q^2}\right]^{\frac{1}{3}} \quad (6)$$

In the particular cases of an electron and a proton one gets

$$\begin{aligned} K_e &= 20R^{\frac{1}{3}}\text{GeV} \\ K_p &= 5\times 10^5 R^{\frac{1}{3}}\text{GeV} \end{aligned} \quad (7)$$

where R is in meters. In any realizable accelerator R is several km which limits the energy to hundreds of GeV for an electron-synchrotron and to about a thousand TeV for a proton-synchrotron. So one needs to explore other types of machines. For high-energy e^+e^- colliders, *linear accelerators* become a very attractive option. This is why all $p\bar{p}$ colliders are circular and all future high-energy e^+e^- colliders will likely be linear. In the high-energy machines several mega watts of power is dissipated in the form of synchrotron radiation around the ring. This power loss is comparable to the power requirements of a small town.

Synchrotron Facilities

A synchrotron radiation facility is based on the technology of charged-particle accelerators. Bunches of charged-particles (usually, electrons) are made to circulate for several hours inside a ring-shaped, long tube under high vacuum. These rings have several beam lines with experimental stations and serve several sets of users simultaneously. Contrary to expectations there are only a few synchrotron facilities to meet the demands of numerous users. This is due to the high cost (about a hundred million US \$) and the specialised technological expertise required to build synchrotrons. Currently, around the world there are about fifty storage rings in operation as synchrotron radiation sources, located in

Figure 1. Booster synchrotron under disassembly.

Figure 2. Bessy - I in Berlin-Wilmorsdorf.*

** BESSY – Berliner Elektronen–spiecherring fuer Synchrotronstrahlung – is a 800 MeV synchrotron.*

twenty-three countries. About a dozen are under construction and another dozen or so are being planned. In Asia there are about twenty synchrotrons laboratories in nine countries: Armenia, China, India, Japan, Jordan, Korea, Singapore, Taiwan and Thailand. This small list leaves out not only many countries but many regions (such as the continents of Africa and Australia) without a single synchrotron facility. India has the expertise and the experience of indigenously building synchrotrons. Two have been built at the Centre of Advanced Technology (**CAT**) in Indore. **Indus-I** is a 450 MeV synchrotron and **Indus-II** is a higher energy 2.0 GeV synchrotron.

The Most Powerful Synchrotrons

The 8.0 GeV **SPring-8** synchrotron is the largest synchrotron radiation source in the world and was completed in 1997 in Hyogo prefecture of Japan. Japan is one of the leading countries along with the United States and the European Union in accelerator-based science research. The SPring-8 belongs to the category of hard X-rays machines, along with the 7.0 GeV Advanced Photon

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Source (**APS**) in Argonne, USA and the 6.0 GeV European Synchrotron Radiation Facility (**ESRF**) in Grenoble, France. Owing to their extremely high energy these synchrotrons have special problems, and have forced the development of new techniques and new devices in the field of optics and detectors to ensure the required high stability of the electron beam.

Accelerator Programmes in India

The accelerator programmes in India have a very long history. It had an early beginning in 1940 when Meghnad Saha developed a 37 inch cyclotron at the Calcutta based Institute of Nuclear Physics, which is now called Saha Institute of Nuclear Physics (**SINP**). In 1950, a 1.0 MeV cyclotron was commissioned at the Tata Institute of Fundamental Research (**TIFR**) in Mumbai. In 1960, a 5.5 MeV Van-de-Graff accelerator was installed at the Bhabha Atomic Research Centre (**BARC**) in Mumbai. In 1978, an indigenously designed and built 224 cm diameter Variable Energy Cyclotron was made operational at the Variable Energy Cyclotron Centre (**VECC**) in Calcutta. Now, there are several Pelletrons such as the 6.0 MeV Pelletron at the Institute of Physics (**IOP**) in Bhubaneshwar and the 14.0 MeV Pelletron at TIFR. The Nuclear Science Centre (**NSC**) in New Delhi has a very energetic 150 MeV Pelletron, which can accelerate very heavy ions to high energies. Very recently a beam of the radioactive isotope beryllium-7 was produced at the NSC. This marks India's entry into an elite group of nations which are doing research with radioactive-ion beams.

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Suggested Reading

[1] Rudolf Peierls, *Radiation in hyperbolic motion*, pp.160-166, in *Surprises in Theoretical Physics*, (Princeton University Press, Princeton, New Jersey, 1979).

[2] World Synchrotron Map, Website: http://www.ssrl.slac.stanford.edu/sr_$sources.html