INFRARED SYNCHROTRON METHODS AND SYSTEMS FOR MONITORING AND CONTROLLING PARTICLE BEAMS IN REAL TIME

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Abstract

We present the methods and infrared position-sensitive detection systems for nondestructive diagnostics and study of charged-particle beams or bunches based on the use of their synchrotron radiation in a wide spectral range. The detection systems contains of the optoelectronic and spectral detectors working in real time with the computer system.

The synchrotron radiation spectrum that is used mainly in the infrared region (wavelength range > 1 µm). The radiation is detected in the spectral region 0.3-45 µm by infrared detectors operating at low temperature or room temperature. Results are presented on the measurement of the number of electrons in the ring bunch, the equilibrium radius and dimensions of the small cross section of bunch, and the angular divergence of the synchrotron radiation relative to the median plane of the ring bunch.

The extension of the spectral range of positively diagnosed synchrotron radiation opens up new possibilities and prospects for solving scientific and applied problems.

INTRODUCTION

Synchrotron radiation of relativistic charge-particles is a well-known effect observed in electron-ring accelerators and storage systems and is widely used in various experiments and investigations, in particular, for passive, nondestructive diagnostics of electron bunches during formation and acceleration of the bunches [1,2]. Synchrotron radiation can be used to measure the current, energy, and geometrical dimensions of electron and proton beams and bunches without affecting the accelerated particles, as well as for nondestructive studies of fast processes. The objectives of this work are as follows – we present the methods and systems of nondestructive diagnostics and study of charged-particle (electron, electron-ion, and proton) bunches (beams) based on the use of their magnetic-bremsstrahlung (synchrotron) radiation in a wide spectral range, from the ultraviolet to the far long-wave infrared region. In this paper, we describe the infrared one-element integration detectors and position sensitive one-coordinate detectors (the sensitive elements are arranged in line) and present the results of measurements with these detectors.

The extension of the spectral range of positively diagnosed synchrotron radiation opens up new possibilities and prospects for solving scientific and applied problems.

INFRARED SOURCES

Synchrotron radiation is a well understood effect which is widely used at electron ring accelerators and storage rings. All charged particles, including protons, emit synchrotron radiation as they move along a curved trajectory in a magnetic field. However, since the proton rest energy E0p (938 MeV) is larger than the electron rest energy E0e (0.511 MeV) by a factor of 1835.6, the intensity of the synchrotron radiation for protons is lower by the same factor for a given particle energy and curvature of the trajectory. Therefore, for the energies available until recently at proton accelerators, synchrotron radiation has hardly been used at all. This explains the limited number of publications on this topic. Such publications have begun appearing only since the late 1970s and deal with the production of synchrotron radiation by the 400 GeV SPS proton synchrotron at CERN (synchrotron radiation at the edges of the displacement magnets at wave-lengths 0.6 µm). The construction of accelerator-storage-ring complexes like SSC or LHC for protons of energy 3-20 TeV may significantly effect the monopoly of electron ring accelerators as the main producers of synchrotron radiation. Analysis of the synchrotron radiation spectra of proton ring accelerators at the leading accelerator laboratories around the world shows that the bulk of the spectral distribution of the radiation for protons of energy up to 1 TeV lies in the infrared region. Estimating the intensity of the proton radiation and comparing it with that of the synchrotron radiation of low-energy electrons at, for example, the JINR accelerator – compressor electron-ring bunch (see we find that the techniques and systems of infrared synchrotron diagnostics developed for the JINR accelerator and later used in accelerator experiments may also be useful for the diagnostics of proton beams with energies above 100 GeV. So far we know of no cases of diagnostics of proton beams with proton energy above 400 GeV. The calculation of the characteristics of synchrotron radiation and the choice of techniques and diagnostics systems have been made and demonstrated for the example of the ring-shaped bunches during bunch compression in the high-current low-energy accelerator – compressor of ring-shaped electron (electron-ion) bunches are based on the measurements of synchrotron radiation [1]. The spectrum of synchrotron radiation from the compressor (electron energy ΔE ≈

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2.5-20 MeV, electron orbit ΔR ≈ 40-4 cm) corresponds largely to the far-infrared range. An important feature of synchrotron radiation is the fact that its characteristics can be predicted theoretically and an exact quantitative description of it can be obtained. The spectral distribution of the instantaneous power of synchrotron radiation emitted by an ultrarelativistic particle of energy E moving along a circular orbit of radius R in the wavelength λ per unit wavelength interval is given by the expression.

METHODS

Basing on these methods there were elaborated measurement systems for the diagnostics of current and geometrical ring parameters [1,2].

Generally number electrons Ne of proportionally complete the synchrotron-radiation intensity of a ring:

$$N_e = \frac{U_{sr} G_{sr}}{S} \left(\int_0^\infty w(\lambda)\, \varepsilon(\lambda)\, \tau(\lambda)\, d\lambda \right)^{-1}.$$

where:

Usr – electrical signal on the detector synchrotron radiation proportional to radiation intensity, got on the detector and registered by it, V;

S – calibration constant of the detector, its integrated sensitivity expressed in volts on unit of falling intensity and measured in calibration experiments;

Gsr – geometrical factor determined by geometry of experiments and angular distribution of synchrotron radiation intensity;

$w(\lambda)$ – radiation intensity of one electron;

$\varepsilon(\lambda)$ – relative spectral sensitivity of the detector;

$\tau(\lambda)$ – spectral transmission of intermediate optical environments.

The constant S is defined on a thermal source, at which, as is known, spectral distribution of radiation intensity is close to distribution of synchrotron-radiation intensity. As a reference source tungsten tape lamp calibrated on an absolutely black body was used.

The geometrical factor is defined on measured angular divergence of flow synchrotron radiation rather median plane of the ring-shaped bunch:

$$G_{sr}(\theta) = \frac{1}{w(0)} \int w(\theta) d\theta.$$

where

w(0) – intensity of synchrotron radiation in a median plane of a bunch;

w(θ) – measured experimentally distribution of a flow of radiation in function of a corner θ between a direction of radiation and median plane of the ring-shaped bunch.

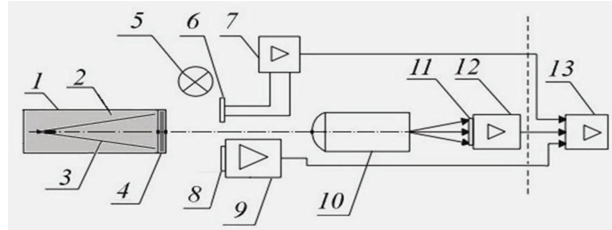

Figure 1: Typical diagram of the SR-diagnostics.

1 – channel of SR;
2 – vacuum;
3 – SR-beam;
4 – window for extracting SR;
5 – reference source;
6 – precision integral detector;
7, 9, 12 – amplifier;
8 – one-coordinate detector of SR-beam;
10 – long-focal-length optical channel;
11 – one-coordinate detector of the profile of the proton-beam;
13 – electronic equipment for accumulating and processing information using a computer.

The measurement suite is formed from a series of computerized optoelectronic and spectrometric detecting systems working in real time on-line to a computer. Those systems contain current-induction sensors and radiation detectors: for gamma rays, characteristic x-rays, and synchrotron infrared radiation. The suite measures several parameters simultaneously: current, energy, geometry, and so on, which characterize the formation and compression of a ring bunch of relativistic electrons and involves the interaction of the charged particles (electrons and heavy ions) in the compressor.

The diagnosis of the charged-particle bunches is analogous to that for the electronuclear plant and involves the following operations.

The infrared radiation beam 3 is extracted through a special heated high-vacuum window 4 [3], which passes infrared radiation over a wide wavelength range, from the planar-cylindrical chamber 1 in the compressor (Fig. 1), which is generated by the bunch 2 of relativistic electrons (the object). The infrared radiation at the output from the compressor is recorded by the noise-immune precision detectors 6 and 7 [4], which are located close to the window 4 and can measure the discrete or integral infrared intensities in various parts of the spectrum. Part of the flux passes to the input pupil of the long-focus wide-band mirror-lens optical channel 9 [5], which transports the radiation with minimal loss to a set distance (over 2.5 m) and transfers it to the detector. The radiation is focused either as an image of the small cross section of the bunch on the sensitive surface of the coordinate detector 10 [6], which measures the geometrical parameters of the ring and the electron distribution over the cross section, or else as an image of the input pupil of the optical channel on the sensitive surface of the one-element precision electron number detector (one of the detectors 6 and 7).

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The infrared radiation is recorded by the detector units 6, 7, and 10, which convert the intensity to a signal that is isolated from the background of the pulsed electromagnetic and radiation interference from the accelerator and is amplified in units 8, 11, and 12. The amplified analog signal passes along the cable highway to the control panel, where there are electronic units for recording, processing, and storing the information 13. The processed results are output in the required form and are stored in the computer.

The controlled source 5 is used to check and calibrate the detectors.

Number of Charge- articles

The electron number measurement method is based on the direct dependence of the synchrotron radiation intensity on the electrons number and the synchrotron radiation registration is made in the spectral region $\lambda >> \lambda c$, when the radiation intensity is independent of the energy of electrons. If the total power W of the radiation of the e-bunch is proportional to the number Ne of electrons in the ring bunch, for a given number of electrons the total power of the radiation is $W = Ne \times w$. The electrons number Ne in the ring bunch can be calculated if one-electron synchrotron radiation power w is known and synchrotron radiation total power W is measured:

$Ne = W / w = [USR / S] \times f(E, R, G, \lambda)$.

The power of the radiation of a single electron for $\gamma >> 1$ is given by

$w = \int \lambda d\lambda = 4.6 \times 10^{-16} \gamma^4 R^{-2} [cm]$.

The total synchrotron radiation power can be determined if we know: the signal on the radiation detector – USR; the calibration constant of the detector – S; the energy electrons – E; the orbit radius – R; the coefficient of synchrotron radiation flow using, from G – geometrical factor determined by solid angle of the synchrotron radiation detector; relative spectral characteristic $\varepsilon(\lambda)$ of the detector; the coefficient of spectral passing $\tau(\lambda)$ of interval pass limits environment (window, filters, optics) and the synchrotron radiation polarization properties. In general case the signal on the radiation detector-receiver can be the following:

$USR = Ne\ S\ G \int w(\lambda)\ \varepsilon(\lambda)\ \tau(\lambda)\ d\lambda$.

where: S is the calibration constant of the detector (V/W), measured with the help of the known methods at the thermal source – tungsten filament lamp. There are two variants of synchrotron radiation intensity measurement: the approximate one when the radiation is measured only in the median plane of the electron ring with the detector and the more precise one when the detectors system involves the greater part of the solid angle, where the most part of the synchrotron radiation is concentrated. The first method is good by simplicity of the apparatus and bad by the absence of operative, for every accelerator pulse, information about the angular distribution of the synchrotron radiation.

Geometrical Parameters

Since a bunch of the charged particles in an accelerator can be considered as an ensemble of oscillators with three degrees of freedom (longitudinal (synchrotron) and two transverse (betatron) – radial and axial ones), the diagnostic set must provide the measurements of the corresponding geometrical parameters of the bunch and possibility of observing the bunch dynamics. The method of measuring the sizes of the bunch and its location inside the accelerator, as well as studies of the bunch dynamics during the compression involves the facilities for extraction of synchrotron radiation from the accelerator chamber, its transportation, and detection. The appropriately reduced image of the bunch cross section is focused on and recorded by a detector unit with sensitive elements arranged in line.

Angular Divergence

An important parameter for the diagnostics of a ring bunch is the angular divergence of the synchrotron radiation in the direction perpendicular to the median plane of the ring bunch. Measurement of this quantity gives information about the electron energy and angular distribution (axial betatron oscillations). A method has been developed to measure the divergence of the radiation beam and the characteristics related to this divergence. This method is based on repeated (throughout the acceleration cycle) measurement of the intensity of the synchrotron radiation as it exits the accelerator chamber by means of an infrared detector whose length covers most of the synchrotron radiation flux in the direction perpendicular to the plane of rotation of the charged particles.

This technique makes it possible to:

1. Estimate the electron energy in the bunch.
2. Measure the power of the synchrotron radiation, taking into account its actual angular distribution, thereby raising the accuracy of absolute measurements of the number of electrons in the bunch.
3. Use the nature of the broadening of the angular distribution of synchrotron radiation to estimate the frequency of betatron oscillations of electrons in the bunch and the intensity of the ion component of the bunch loaded with ions.

EXPERIMENTAL APPARATUS

The diagnostics of the parameters of the ring bunch are performed simultaneously by several information-measuring systems which realize the various methods listed in the preceding section. Synchrotron radiation from the electron ring is extracted through an infrared window of the vacuum chamber of the accelerator, then it is transported along the optical channel over the given

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distance and is received by a detectors unit with a power sources. The detector signals are registered and processed by an electronic facility, and then transferred to a computer for the real-time processing. In the immediate vicinity of the accelerator, there is only the detector units, which includes a single-element and multielement coordinate infrared detectors with a preamplifier in each of the recording channels, a cryogenic system (in the case when the detector is cooled to the temperature of the liquid nitrogen), and a power sources. The detectors unit can be moved in the image plane by electric motors, which is remotely controlled by a unit. The processing facilities are outside the region of the radiation damage. The synchrotron light is extracted from the accelerator through windows made of various optical materials. The optical channel designed for the extraction and transportation of synchrotron radiation includes an output window and a long-focus wide-band optical mirror channel; at the output of the channel, radiation is focused on the sensitive surface of the coordinate detector. The synchrotron radiation extracted from the accelerator is recorded by three independent infrared detection systems forming a single information-measuring complex. Each system performs a specific task, operating synchronously on a common time scale. The device with a single-element detector is designed for measuring the absolute number of electrons. The geometrical parameters of the bunch are measured using a system containing a multi-element coordinate detector system located at the focus of the optical channel. The angular divergence of the synchrotron radiation and its intensity are measured by an infrared coordinate detector with linear arrangement of the elements. The information obtained from the measuring systems is collected and processed in the units, which incorporate a computer. This information significantly raises the overall accuracy and information content of the measurements. The choice of detectors for the diagnostics systems is determined by the intensity and spectral characteristics of the recorded synchrotron radiation, and also by the conditions of operation of the accelerator. The main requirements in choosing the detectors were the following:

- High spectral sensitivity in the wavelength range $\lambda \approx$ 0.4-40 μm.
- Time resolution (speed of response) $t = 0.1\text{-}5 \cdot 10^6$ s.
- Simplicity of operation (absence of complicated cryogenic systems).

Various types of infrared collector were considered. Five types of photocollector sensitive to the given region of the infrared spectrum were proposed to conform with the above requirements. The synchrotron radiation of the electrons can be recorded either by all the measuring systems simultaneously or by each separately. The radiation intensity is recorded by detectors and output as an analog signal, which is preamplifier to the required amplitude and fed via a cable to the control panel of the accelerator, where it is transformed into digital from and processed by computer. The measurement channels allow repeated (up to 10 times) recording of a ring compression cycle in the compressor of the accelerator. The duration of the measurement date is 0.1 μs. The time interval between successive measurements can be varied from 100 μs and more for a total duration of the synchrotron radiation pulse of about one millisecond.

CONCLUSION

Methods for measuring the current and geometrical parameters and estimating the energy parameters of bunch in ring accelerators using synchrotron radiation in the infrared region are reviewed, together with the information-measuring systems designed to detect synchrotron radiation and realize these methods. The synchrotron radiation spectrum that is used lies mainly in the infrared region. The detection systems incorporate specially designed infrared-optical elements (a high-vacuum window of optical ceramics and broad-band, long-focus optical channels). The radiation is detected in the spectral region $\Delta\lambda = 0.3\text{-}45$ μm by infrared detectors operating at low temperature or room temperature. It should be noted that the range of applicability of these results is fairly broad. Most of the techniques and information-measuring systems described here can be used in the same or slightly altered form at other electron and proton ring accelerators which generate synchrotron radiation, for example, LHC, SPS the synchrotron radiation spectrum at which lies mainly in the infrared region. They are useful both for the diagnostics of bunches and beams during their dynamical development, and for carrying out various types of scientific research and solving applied problems based on the use of infrared synchrotron radiation, including beam diagnostics and research at electron-positron storage rings The objectives of this work are as follows:

- We present the methods and systems of nondestructive diagnostics and study of charged-particle (electron, electron-ion, and proton) bunches and beams based on the use of their magnetic-bremsstrahlung (synchrotron) radiation in a wide spectral range, from the ultraviolet to the far long-wave infrared region.
- We draw attention to the great diversity of problems, both in accelerator experiments (for example, the study of the coherence of synchrotron radiation or of the coherent processes at colliders) and in other, sometimes quite unrelated fields, such as metrology, high-temperature superconductivity, biology, etc., which might be solved by means of infrared synchrotron diagnostics, covering the interval of wavelengths $\Delta\lambda = 0.3\text{-}45$ μm, which is much larger than the spectral range that is widely used at present (basically, the range $\Delta\lambda = 0.3\text{-}1.1$ μm) in various experiments and investigations.
- The extension of the spectral range of positively diagnosed synchrotron radiation opens up new possibilities and prospects for solving scientific and applied problems.

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