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

M. V. Maltseva, TENZOR, Dubna, Russia

A. A. Maltsev, JINR, Dubna, Russia

INTRODUCTION

- Synchrotron radiation (SR) 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, non-destructive diagnostics of electron bunches during formation and acceleration of the bunches. SR 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 non-destructive studies of fast processes.
- The objectives of this work are as follows:
- – we present the methods and systems of non-destructive diagnostics and study of charged-particle (electron, electron-ion, and proton) bunches (beams) based on the use of their synchrotron radiation in a wide spectral range, from the ultraviolet to the far long-wave infrared (IR) region;
- – we describe the IR 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 SR opens up new possibilities and prospects for solving scientific and applied problems.

INFRARED SOURCES

Analysis of the SR 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 IR region.
Estimating the intensity of the proton radiation and comparing it with that of the SR of low-energy electrons, for example, at the JINR accelerator – compressor electron-ring bunch (see we find that the techniques and systems of IR 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 SR 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 SR.
The spectrum of SR from the compressor (electron energy $\Delta E \approx 2.5$-20 MeV, electron orbit $\Delta R \approx 40$-4 cm) corresponds largely to the far IR range.
An important feature of SR 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 SR 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.
Generally number electrons *Ne* of proportionally complete the SR 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:
U_{sr} – electrical signal on the detector SR 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;
G_{sr} – geometrical factor determined by geometry of experiments and angular distribution of SR intensity;
$w(\lambda)$ – radiation intensity of one electron;
$\varepsilon(\lambda)$ – relative spectral sensitivity of the detector;
$\zeta(\lambda)$ – spectral transmission of intermediate optical environments.

METHODS

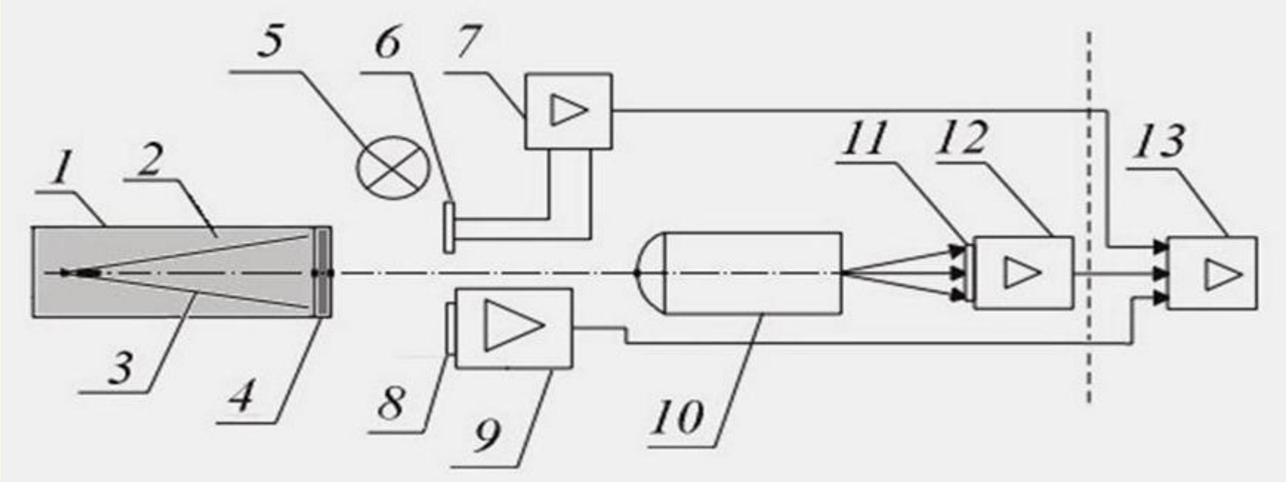
The constant S is defined on a thermal source, at which, as is known, spectral distribution of radiation intensity is close to distribution of SR intensity. As a reference source tungsten tape lamp calibrated on an absolutely black body was used.
The geometrical factor is defined on measured angular divergence of flow SR 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 SR 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.**

- **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 IR 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.**

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.

Number of charge-particles

- The electron number measurement method is based on the direct dependence of the SR intensity on the electrons number and the SR 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 N_e of electrons in the ring bunch, for a given number of electrons the total power of the radiation is $W = N_e \times w$. The electrons number N_e in the ring bunch can be calculated if one-electron SR power w is known and SR total power W is measured:
- $N_e = W / w = [USR / S] \times f(E, R, G, \lambda)$.
- 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 SR power can be determined if we know: the signal on the radiation detector – U_{SR}; the calibration constant of the detector – S; the energy electrons – E; the orbit radius – R; the coefficient of SR flow using, from G – geometrical factor determined by solid angle of the SR 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 SR polarization properties.
- In general case the signal on the radiation detector-receiver can be the following:

  $U_{SR} = N_e \, S \, G \int w(\lambda) \, \varepsilon(\lambda) \, \tau(\lambda) \, d\lambda$,
- 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 SR 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 SR 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 SR.

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 SR 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 SR 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 SR as it exits the accelerator chamber by means of an IR detector whose length covers most of the SR 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 SR 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.
SR from the electron ring is extracted through an IR window of the vacuum chamber of the accelerator, then it is transported along the optical channel over the given 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 IR detectors with a preamplifier in each of the recording channels, a cryogenic system (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.

EXPERIMENTAL APPARATUS (cont)

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 SR 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 SR extracted from the accelerator is recorded by three independent IR detection systems forming a single information-measuring complex.
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 SR and its intensity are measured by an IR coordinate detector with linear arrangement of the elements.

Main requirements in choosing the detectors

The choice of detectors for the diagnostics systems is determined by the intensity and spectral characteristics of the recorded SR, 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 $\lambda \approx 0.4\text{-}40$ μm.**
- ✓ **Time resolution (speed of response) $t = 0.1\text{-}5\cdot10^{6}$ s.**
- ✓ **Simplicity of operation (absence of complicated cryogenic systems).**

CONCLUSIONS

- Methods for measuring the current and geometrical parameters and estimating the energy parameters of bunch in ring accelerators using SR in the IR region are reviewed, together with the information-measuring systems designed to detect SR and realize these methods.
- The SR spectrum that is used lies mainly in the IR region.
- The detection systems incorporate specially designed IR-optical elements (a high-vacuum window of optical ceramics and broadband long-focus optical channels).
- The radiation is detected in the spectral region $\Delta\lambda = 0.3–45$ μm by IR 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 SR, for example, LHC, SPS, the SR-spectrum at which lies mainly in the IR region.

THANK YOU FOR ATTANTION!