# CHARACTERISTICS OF SYNCHROTRON RADIATION OF STORAGE RING NESTOR AND ITS APPLICATIONS

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The results of calculations of the basic SR characteristics, generated from bending magnets of the storage ring NESTOR are presented. The methods of parameter measurements of a circulating beam with SR are considered. The possible areas of SR application of the storage ring NESTOR are given.

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## INTRODUCTION

The interest to the synchrotron radiation sources grows year by year [1]. Unique synchrotron radiation (SR) properties have made it the powerful tool in realization of scientific researches and solving of applied tasks. SR is the excellent tool for diagnostics of a beam of the charged particles.

In NSC KIPT the design of a generator of the X-ray NESTOR on the basis of Compton scattering of an intensive laser beam on electrons, which circulate in the storage ring is carried out [2]. Besides generation of hard X-ray photons in the storage ring NESTOR it is supposed to utilize SR from bending magnets.

## CHARACTERISTICS OF SYNCHROTRON RADIATION OF NESTOR

At calculations of the radiation characteristics the following parameters of the projected storage ring NESTOR were used:

- energy of electron beam is 225 MeV
- the maximum stored current is 0.36 A
- bending radius in magnets is 0.5 m

The radiation has a continuous power spectrum. Its intensity begins exponentially decrease, since so-called critical energy of photons [3]:

$$\varepsilon_c[KeV] = \frac{3\hbar c\gamma^3}{2\rho} = 2.218\frac{E^3[GeV]}{\rho[m]}, \tag{1}$$

where $\gamma = E/mc^2$ is the relativistic factor, $\hbar$ is the Planks constant, *c* is the light velocity.

Half of photons, from emitted electron, are concentrated in the region of an energy spectrum up to critical energy, half down. In a Fig. 1 the dependence of critical energy of photons on electron energy in operation region of NESTOR is shown. So, the critical energy of the NESTOR bending magnet radiation will be in the range of value 0.5…50 eV (infrared, visible and VUV ranges).

The spectral and angular distribution of SR is described by expression [3]:

$$\frac{dN}{d\Omega}[photon/s/sterad] = \frac{3\alpha\gamma^6}{4\pi^2}\frac{\omega}{\omega_c}\left(\frac{1}{\gamma^2}+\psi^2\right)\times$$

$$\left[K_{2/3}^2(\zeta)+\frac{\psi^2}{\left(1/\gamma^2+\psi^2\right)}K_{1/3}^2(\zeta)\right]\frac{I}{e}\frac{\Delta\omega}{\omega}, \tag{2}$$

where $\zeta = \frac{\omega\left(1+\gamma^2\psi^2\right)^{2/3}}{2\omega_c}$, α is fine structure constant, ω is radiation frequency, $\omega_c$ is critical radiation frequency, ψ is characteristic vertical opening angle, *e* is electron charge.

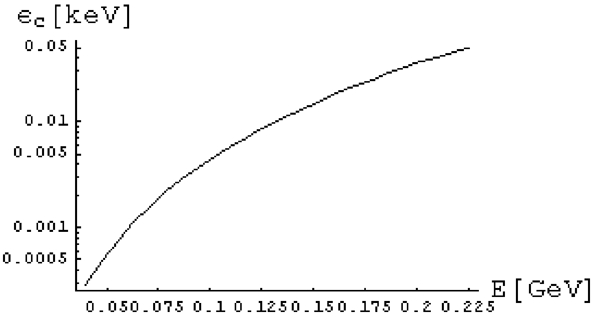

***Fig. 1.*** *Critical energy of photons vs electron energy in operation energy range of NESTOR*

Photon number $dN/d\Theta$, of given energy emitted in 1 mrad of horizontal angle per second in an interval of wavelengths $\Delta\lambda/\lambda$ is received by integrating spectral angular SR distribution (2) on a vertical angle and multiplying on number of particles in a beam (current of beam). In practical units it is given by [3]:

$$\frac{dN}{d\Theta}[photon/(s\cdot mrad)] = \\ = 2.457\cdot 10^{16}\cdot E\cdot I\cdot G_1(\lambda_c/\lambda)\cdot\Delta\lambda/\lambda \tag{3}$$

where $G_1(\lambda_c/\lambda) = \frac{\lambda_c}{\lambda}\int\limits_{\lambda_c/\lambda}^{\infty} k_{5/3}(x)d(x)$, λ is wavelength of SR, $\lambda_c = 5.59R/E^3$ is critical wavelength of SR.

At a current of 0.36 A, and beam energy of 225 MeV the maximum flux of photons is equal to 1.4× $10^{12}$ (see Fig. 2).

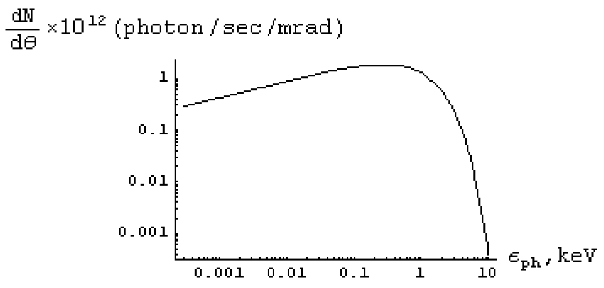

***Fig. 2.*** *Photon flux vs on its energy*

An opening angle of SR *ψ(ω)* can be approximated with expressions [3]:

$$\psi(\omega)=\begin{cases}\dfrac{1}{\gamma(\omega_c/\omega)^{1/3}} & npu\ \omega<<\omega_c\\ \dfrac{1}{\gamma} & npu\ \omega=\omega_c\\ \dfrac{1}{\gamma(\omega_c/\omega)^{1/2}} & npu\ \omega>>\omega_c\end{cases}\qquad(4)$$

The radiation in a low energy part of the spectrum will be concentrated within angle which is bigger a little then $1/\gamma$ and, otherwise, in high energy part of the spectrum the value of radiation opening angle will be smaller. So, in the radiation directivity diagram in the center of the spectrum radiation will be harder then to the boundaries. It is clear that main part of bending magnet radiation of NESTOR will be concentrated within solid angle of 0.012…0.0023 rad dependently on electron beam energy. The power of photons beam depends on number of radiated photons in view of their energy and multiplication to number radiating electrons, i.e. current of an electron beam.

The spectral power, integrated on all vertical angle per milliradian of a horizontal angle, in practical units, is given by [3] (see Fig. 3):

$$P\left[\frac{mW}{mrad}\right]=8.73\cdot 10^{3}\,\frac{E^4[GeV]}{\rho\,[m]}\,I[A]\,G_2(y)\,\frac{\Delta\lambda}{\lambda},\qquad(5)$$

$$G_2(y)=y^2\int_y^{\infty}K_{5/3}(x)dx,\quad y=\frac{\lambda_c}{\lambda}.$$

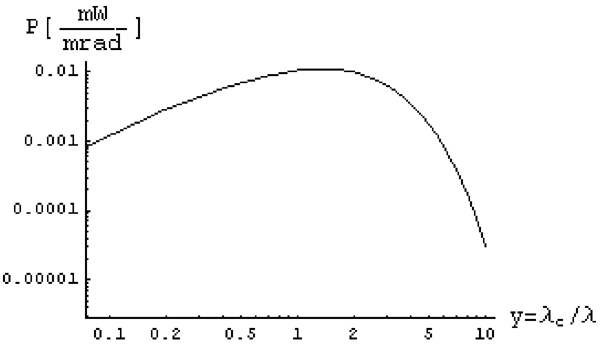

***Fig. 3.*** *Spectral power of radiation*

The complete radiated power along whole orbit for NESTOR at electron beam energy 225 MeV will be:

$$P_{SR}[kW]=\frac{88.5E^4[GeV]I[A]}{\rho\,[m]}=0.163\qquad(6)$$

Source spectral brightness is equal to emitted photon number per solid angle unit per second from unit of square in bandwidth *Δλ/λ* depends on beam sizes $\sigma_x$, $\sigma_z$ and its angle divergence as follow [3]:

$$B_\lambda\,[photons/(0.1\%BW\cdot mm^2\cdot mrad^2\cdot s)]=$$
$$=N_\lambda/\sigma_x\cdot\sigma_z\left(\psi_\lambda^2+\sigma_z'^2\right)^{1/2}\qquad(7)$$

where $\psi_\lambda$ [mrad] is angle divergence of SR, $\sigma_z'$ [mrad] is vertical RMS divergence of electron beam in a radiation point.

Taking into account electron beam sizes at a radiation point $\sigma_x$=0.226 mm, $\sigma_z$=0.13 mm SR divergence ψ=0.012…0.0023 mrad and electron beam divergence $\sigma_z'$=0.13 mrad, we get the maximum value of the spectral brightness from NESTOR bending magnet $B_\lambda=3.9\times 10^{12}\ldots 2\times 10^{13}$.

## NESTOR SR UTILIZATION

It is supposed that one of SR channels, of electron storage ring NESTOR, will be used for diagnostics of an electron beam parameters. With the SR electron beam cross-section, angular divergence of the particles, and length of bunch will be obtain [4].

Determination of the beam cross-section will be carried out with optical elements and of the detector (charge coupled device (CCD)). SR emitted tangentially at the bending magnet is extracted from the vacuum chamber through a window. A lens or set of lenses is then used to form an image of the source point on a CCD. The main advantage of a scientific-grade CCD are low read-out noise (less than 10 electrons per pixel, when cooled (typically to between -20ºC and -120ºC) and read-out slowly); low dark current (from 2 to 40 electrons/hour per pixel, when cooled); spatial resolution is about 15 µm; high quantum efficiency (for thinned, backside illuminated CCDs, the peak quantum efficiency can exceed 80 %, and even for conventional CCDs, values of over 30 % are typical) [5].

A similar measurement system was developed and applied at Kharkov electron storage ring N-100 [6]. The system used optical system, two dissectors LI-603 and facility for automatic measurement. The system allowed to measure electron beam sizes in range 0.5…9.9 mm at electron current changes of about $5\times10^{-3}$…5 A. Electronic equipment provided measurement accuracy of about 2 % while dissector accuracy was strongly depended on electron beam current (income SR flux) and was in range 0.1…5 %.

It is also possible to observe the SR directly without using focusing elements. In this case one measures the angular distribution of the particles in the beam. SR is extracted from the vacuum chamber through a window of the storage ring with minimal possible losses on intensity. There are two variants of measuring of SR intensity, when the radiation is measured only in a median plane of a bunch by one sensor, or when the system of sensors sweeps a solid angle, where the main part SR focused. For registration SR (the measuring its angular distribution) the measuring systems with detectors of various spectral sensitivity are designed and created. Light-sensitive photodetectors (silicon photodiode is operate in spectral region 0.4…1.1 μm, detector of lead-selenide in spectral region 0.8…4.6 μm) allows to ensure measuring intensity of SR with relative accuracy about 0.2 % and can register number of particles in region $10^7…10^{13}$ [7].

The bunch length can be measured by observing the time structure of the emitted radiation. Since the light pulse observed from each individual particle is very short the time distribution of the radiation reflects directly the longitudinal bunch shape. A photon detector is needed to measure this distribution. The resolution of measuring system of the longitudinal size with SR in principle is not limited due to properties of this radiation and is completely determined by opportunities of measuring devices. For example in NESTOR ring an electron bunch length will be of about $10^{-2}$ m. So, measuring equipment should provide measurement of pulsed with duration of about $3.3\times10^{-11}$ s with repetition rate of about $7.2\times10^8$.

SR is ideal calibrating instrument for vacuum ultraviolet area of a spectrum. On the NESTOR it is possible to create a beamline and to use it for absolute calibration of dosimeters, detectors of electromagnetic radiation in VUV area of a spectrum.

The opportunities of calibration and absolute measurements are connected to SR applications in atomic physics, spectroscopy of multicharged ions, by photoelectronic spectroscopy of gases etc.

SR is successfully applied in research of solids, in VUV spectroscopy of non-conductors, semiconductors and metals. The high degree of SR polarization allows to research an anisotropy of electron properties of a solid and effectively to apply methods of an ellipsometry in VUV area of a spectrum.

SR from bending magnets of the storage ring NESTOR one may use for research in biology and medicine.

SR from bending magnets with a wavelength about 100 Å is applied for researches of dynamics of proteins, of spectroscopy of biopolymers. SR with a spectrum from infrared to a visible range ($\lambda\approx3$ μm…500 Å) will find a use in biomedicine, microsurgeries and phototherapies [8].

## CONCLUSIONS

Thus, SR from bending magnets of the storage ring NESTOR with such parameters as: critical energy in range 0.5…50 eV, the maximum flux of photons is $1.4\times10^{12}$ [photon/(s·mrad)], the spectral brightness is $3.9\times10^{12}…2\times10^{13}$ [photon/(0.1%BW·mm$^2$·mrad$^2$·s)] can be widely used for diagnostics of an electron beam parameters, research of solids, VUV spectroscopy of non-conductors, semiconductors and metals, research in biology and medicine.

## REFERENCES

1. C. Kunz. *Synchrotron Radiation Techniques and Applications.* Moskow: “Mir”, 1981, p. 9-36 (in Russian).
2. P. Gladkikh, I. Karnaukhov, A. Zelinsky, et all. Intense X – Ray Sources Based on Compton Scattering in Laser Electron Storage Ring // *Problems of Atomic Science and Technology, series: Nuclear Physics Investigation.* 2002, v. 40, №2, p 72-74.
3. J. Murphy. *Synchrotron Light Source*. Data Book, BNL-4233, 1989.
4. A. Hofmann. Characteristics of Synchrotron Radiation *// CAS CERN 98-04,* 1998, p. 1-30.
5. Ernst-Eckhart Koch. *Handbook on synchrotron radiation*. North-Holland Company, 1983, v. 1A.
6. V. Teslenko, A. Zelinsky. System of automatical measurement of beam sizes in an electron storage ring //*Pribory i Technica Experimenta*. 1987, №5, p. 41-43 (in Russian).
7. A. Mal'tsev. Infrared synchrotron diagnostics as a new direction in physics and technique of accelerating experiment // *Physics of Elementary Particles and Atomic Nuclei.* 1996, v. 27(3), p. 797-848, (in Russian).
8. Materials of international working conference «Synchrotron source UINR: prospects of researches» // *UINR.* 1999, Dubna (in Russian).

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## ХАРАКТЕРИСТИКИ СИНХРОТРОННОГО ИЗЛУЧЕНИЯ НАКОПИТЕЛЯ НЕСТОР И ЕГО ПРИМЕНЕНИЕ

***В.Е. Иващенко, И.М. Карнаухов, Н.В. Ковалёва, А.А. Щербаков, А.Ю. Зелинский***

Проведен расчет основных характеристик СИ, генерируемого из поворотных магнитов накопителя электронов НЕСТОР. Рассмотрены методики проведения измерений параметров циркулирующего пучка с помощью СИ. Приведены возможные области применения СИ накопителя НЕСТОР.

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## ХАРАКТЕРИСТИКИ СИНХРОТРОННОГО ВИПРОМІНЮВАННЯ НАГРОМАДЖУВАЧА НЕСТОР ТА ЙОГО ВИКОРИСТАННЯ

***В.Е. Іващенко, І.М. Карнаухов, Н.В. Ковальова, О.О. Щербаков, А.Ю. Зелінський***

Проведено розрахунок основних характеристик СВ, що генерується з поворотних магнітів нагромаджувача електронів НЕСТОР. Розглянуто методики проведення вимірів параметрів циркулюючого пучка за допомогою СВ. Приведено можливі області застосування СВ нагромаджувача НЕСТОР.