SYNCHROTRON RADIATION FROM THE NESTOR STORAGE RING

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The main characteristics of synchrotron radiation from the generator X–ray NESTOR are presented. NESTOR is a New Electron Storage Ring with electron energy from 40 up to 225 MeV and circumference 15.418 m . Areas of application of photon beams from infrared up to vacuum ultraviolet region are considered in the work.

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1. INTRODUCTION

Synchrotron radiation (SR) is electromagnetic radiation generated by the acceleration of ultrarelativistic (i.e., moving near the speed of light) charged particles through magnetic fields.The SR attracts attention of researchers by its extremely wide range of particular properties such as a high radiation power, a pronounced angular directivity, a high degree of polarization and a broad continuous spectrum (from far infrared up to X–ray region), a possibility of exact calculation of characteristics. Because of these unique properties, the SR has recently begun to play a decisive role in intensive development of scientific investigations showing the most promise for physics, chemistry, biology, medicine, microelectronics, tomography, materials science, etc. [1].

A few tens of largest labs of the world are engaged in these investigations, national centres for the use of SR have been built, and cost intensive factories of SR are under construction in the USA, England, France, Germany, Italy, Japan, etc.

At the NSC KIPT in Kharkov, an X–ray generator NESTOR is being constructed around the electron storage ring N–100M, based on Compton backscattering of an intense laser beam by electrons, which circulate in the storage ring [2]. Besides generation of hard X–ray Compton photons in the storage ring NESTOR, the SR will also be extracted from the bending magnets of the facility.

2. CHARACTERISTICS OF SYNCHROTRON RADIATION OF NESTOR

The layout of the storage ring NESTOR under construction with dedicated SR extraction channels, as well as the parameters and basic characteristics of SR are given in Fig.1 and table, respectively [3].In Fig.1 are shown the 1–X-ray channel and 2–channels of SR.

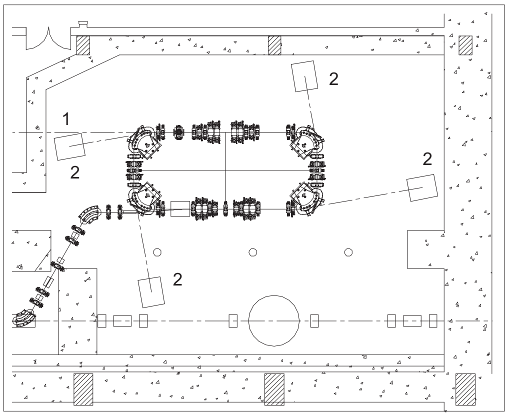

Fig.1. *Layout of the storage ring NESTOR with possible channels of SR*

The SR properties such as spectral distribution, polarization, angular divergence, can be exactly calculated from the machine parameters.

The SR beam is emitted by electrons at a tangent to the trajectory and has an angular divergence $\Psi \approx \gamma^{-1}$, where γ is the relativistic factor (ratio of electron energy E in the storage ring to the rest energy of the electron E_0=0.511MeV). The SR has a broad continuous spectrum of radiation from infrared up to X–ray range.

The SR intensity begins to decrease exponentially, starting from the so-called critical photon energy value [4]:

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

where $\hbar$ is Planck's constant, c is the speed of light.

Fig.2 shows the critical photon energy versus electron energy in the operating energy range of the NESTOR storage ring.

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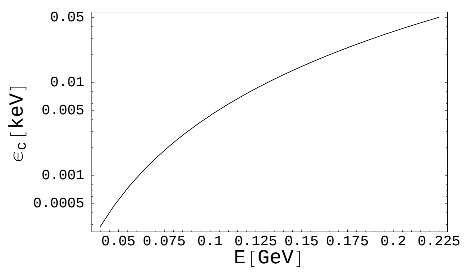

Fig.2. *Critical energy of photons versus electron energy of NESTOR*

So, the critical energy of the NESTOR bending magnet radiation will be in the energy range from 0.5 to 50 eV (infrared, visible and VUV ranges).

The spectral and angular distribution of SR is described by expression [4]:

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

where:

$$\xi = \frac{\omega(1+\gamma^2\psi^2)^{\frac{2}{3}}}{2\omega_c},$$

α is fine structure constant, ω is radiation frequency, ω_c is critical radiation frequency, ψ is characteristic vertical opening angle,e is electron charge.

Parameters and basic characteristics of SR from the storage ring NESTOR

Parameters	Value
Energy of electron beam, E	$40\ldots225$MeV
Maximum stored current, I	0.36A
Storage ring circumference, S	15.418m
Bending radius in magnets, ρ	0.5m
Betatron tunes, Q_x, Q_z	$3.155, 2.082$
RF frequency	700MHz
Harmonics number	36
Electron beam sizes, σ_x, σ_z	$0.226, 0.13$ mm
Electron beam divergence, σ'_z	0.13mrad
Critical energy of photons, ε_c	$0.5-50$ eV
Critical wavelength of SR, λ_c	$245-43671.9\mathring{A}$
Angle divergence of SR, Ψ	$0.012-0.0023$mrad
Maximum power of photon beam, P	0.025W/mrad
Spectral brightness, B_λ	$3.9\times10^{12}-2\times10^{13}$ $photon/(0.1\%BW^\star \times mm^2 \times mrad^2 \times s)$
Maximum flux of photons	$2.4\times10^{11}-1.4\times10^{12} photon/(s\times mrad)$

* where 0.1%BW denotes a bandwidth $10^{-3}\omega$ centered around the frequency ω.

Photon number $dN/d\Theta$, of given energy emitted in 1mrad 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 [4]:

$$\frac{dN}{d\Theta}\left[\frac{photon}{(s\times mrad)}\right] = \tag{3}$$
$$= 2.457\times10^{16}\times E\times I\times G_1\left(\frac{\lambda_c}{\lambda}\right)\times\frac{\Delta\lambda}{\lambda},$$

where:

$$G_1(\lambda_c/\lambda) = \frac{\lambda_c}{\lambda}\int_{\lambda_c/\lambda}^{\infty}K_{5/3}(x)d(x), \tag{4}$$

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 will be equal to 1.4×10^{12}(photon/sec/mrad) (see Fig.3).

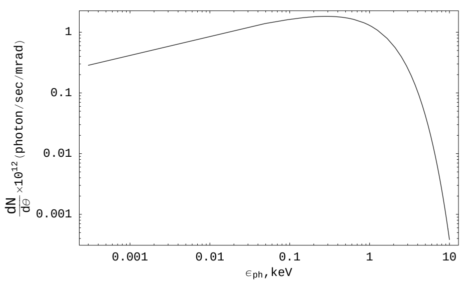

Fig.3. *Photon flux versus energy of photons*

Source spectral brightness is equal to emitted photon number per solid angle unit per second from unit of square in bandwidth $\Delta\lambda/\lambda$ depends on beam sizes σ_x, σ_z and its angle divergence as follow [4]:

$$B_\lambda[photon/0.1\%BW\cdot mm^2\cdot mrad^2\cdot s] = \tag{5}$$
$$= N_\lambda/\sigma_x\cdot\sigma_z\cdot(\psi^2_\lambda+\sigma'^2_z)^{\frac{1}{2}},$$

where ψ_λ is angle divergence of SR, σ'_z 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 $\psi = (0.012 - 0.0023)\,mrad$ and electron beam divergence $\sigma_z^{'} = 0.13\,mrad$, we get the maximum value of the spectral brightness from NESTOR bending magnet $B_\lambda \sim (3.9 \times 10^{12} - 2 \times 10^{13})$.

The Schwinger's equation can be used to calculate the vertical angular spread of the synchrotron radiation and its polarization [5]. The radiation power with polarization parallel to the orbital plane is given by [6]:

$$P_\sigma\left(\lambda, \gamma, \psi, \rho, \Delta\lambda, I_{\rm B}, \Delta\theta\right) = \tag{6}$$
$$= \frac{2}{3} \frac{e_0 \Delta\lambda \Delta\theta I_{\rm B} \rho^2}{\varepsilon_0 \beta \lambda^4 \gamma^4} \left[1 + (\gamma\psi)^2\right]^2 K_{2/3}\left[\xi\left(\lambda, \psi\right)\right]^2$$

and the radiation power with polarization perpendicular to the orbital plane is given by:

$$P_\pi\left(\lambda, \gamma, \psi, \rho, \Delta\lambda, I_{\rm B}, \Delta\theta\right) = \frac{2}{3} \frac{e_0 \Delta\lambda \Delta\theta I_{\rm B} \rho^2}{\varepsilon_0 \beta \lambda^4 \gamma^4} \times$$
$$\times \left[1 + (\gamma\psi)^2\right] (\gamma\psi)^2 K_{1/3}\left[\xi(\lambda, \gamma)\right]^2. \tag{7}$$

The total power is:

$$P_{tot} = P_\sigma\left(\lambda, \gamma, \psi, \rho, \Delta\lambda, I_{\rm B}, \Delta\theta\right) + \tag{8}$$
$$+ P_\pi\left(\lambda, \gamma, \psi, \rho, \Delta\lambda, I_{\rm B}, \Delta\theta\right).$$

The figure 4 demonstrate vertical angular spread of the SR at NESTOR for $100\,nm$ wavelength at $225\,MeV$.

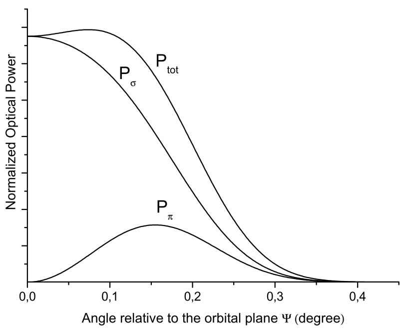

Fig.4. *Vertical angular spread of the SR at NESTOR for* $100\,nm$ *wavelength at* $225\,MeV$

Schwinger's equation is useful to calculate the synchrotron radiation emission of one electron in a perfect orbit, but it does not take into account the electron emittance. This calculated vertical angular distribution of the synchrotron radiation has to be convolved with the vertical angular spread of the electron beam and also the angular spread caused by the finite vertical beam size, which depends on the distance from the tangent point. Therefore in real experiments with definite requirements vertical angular distribution of the synchrotron radiation and its polarization will be differ from theoretical calculations[6],[8].

3. APPLICATION OF SR FROM NESTOR

By now the scientists have gained great experience in problem definition and realization of investigations with the use of SR.

It is supposed that one of the SR beamlines of the electron storage ring NESTOR will be used for diagnostics of electron beam parameters. With the SR the electron beam cross-section, the angular distribution of particles, and the bunch length will be determined. The transverse size is obtained by forming an image of the beam cross section by means of the emitted SR. The angular spread of the particles in the beam can be obtained by direct observation of the radiation.Measuring both beam cross section and angular spread gives the emittance of the beam.The emittance of the beam in NESTOR by $E = 225\,MeV$ is $\epsilon = 0.1855 \times 10^{-6}\,m \cdot rad$. The longitudinal particle distribution is directly obtained from the observed time structure of the emitted radiation [7].The bunch length is $\sigma_l = 0.1708 \times 10^{-2}$.

Among many practical applications of SR, of most interest is its usage in experiments on vacuum ultraviolet solid-state spectroscopy. These experiments provide a very important information for an understanding of the electronic structure of solids, because in this range the basic structure characteristic of a solid body is concentrated, viz., excitons, plasmons, band-to-band transitions of valence electrons.

Photoelectron spectroscopy (PES) consists in measuring the energy distribution of photoelectrons escaped from the solid under study at its irradiation with monochromatic photons. The photoelectron spectra display (to an accuracy of the matrix elements of excitation) the density of occupied electronic states of the matter under study. The photon energy range used $(4 - 100\,eV)$ makes it possible to investigate the valence band and shallow core levels.

The storage ring NESTOR may accommodate the PES station, which will be intended for integrated insitu studies of thin films, multilayer thin-film structures and fresh spalls of crystals. The special feature of this station will lie in the possibility of measuring spectra at photon energies between 10 and $50\,eV$, practically not used at most of the foreign PES stations.

One of the unique properties of SR is its high degree of polarization. The variation in the state of polarization of light at reflection forms the basis for the method of determining the optical properties of materials. The energy range of the storage ring NESTOR makes it possible to use efficiently the ellipsometry methods (determination of optical constants, thickness of thin films, study of adsorption, oxidation of semiconductor and metal surfaces, etc.) in the UV range of the spectrum $(5 - 50)\,eV$, and to investigate both bulky and thin-film, isotropic and anisotropic samples.

The SR is an ideal calibrating instrument for ultra-violet range of the spectrum. The main parameters of the storage ring NESTOR influencing on flux of SR, are determined with accuracy : repetition rate $\frac{\Delta f}{f} = 10^{-6}$; energy of electron $\frac{\Delta E}{E} = \pm 2.981 \times 10^{-6}$ for $E = 60\,MeV$, $\frac{\Delta E}{E} = \pm 6.208 \times 10^{-4}$ for $E = 225\,MeV$; magnetic field in the radiation point $\frac{\Delta H}{H} = 1.0 \times 10^{-4}$. The spectral dependence of accuracy of definition flux of the storage ring N-100 is on some orders worse than in NESTOR. [9] So, it is planned to create a metrological channel at the NESTOR and to use it for absolute calibration of dosimeters, detectors of electromagnetic radiation in the VUV region of the spectrum. [10]

The SR from bending magnets of the storage ring NESTOR can be used for studies in biology. [11]

One of the applications of SR from the storage ring NESTOR is the infrared fast spectromicroscopy with a high spatial resolution of up to $3 - 5\,\mu m$ [11]. A high luminosity of the light source allows one to reduce substantially the measurement time (by a factor of 10^3) as compared with traditional Fourier spectrometers. Another SR application is the infrared (IR) spectroscopy of biological objects, living tissues, etc. The analysis of IR absorption spectra makes it possible to find out the size, concentration and composition of crystals and, thus, to identify various bone diseases.

Thus, the SR from NESTOR bending magnets enables one to carry out basic research and applied technological work.

4. CONCLUSIONS

The commissioning NESTOR is expected at the end of 2008. Numerical values of synchrotron radiation characteristics are obtained for the storage ring NESTOR. The characteristics demonstrate that the given storage ring can operate in infrared, visual and ultra-violet radiation ranges ($0.5 - 50\,eV$). The SR is characterized by a sharp directivity ($\Psi \preceq 0.012 - 0.0023\,mrad$), a high degree of polarization, and can be used to advantage as a light source for conducting investigations in the fields of solid-state physics, metrology and biology.

REFERENCES

1. C. Kunz. *Synchrotron Radiation. Techniques and Applications*. Moskow: "Mir", 1981, p.9-36 (in Russian).
2. P. Gladkikh, I. Karnaukhov, A. Zelinsky. Intense X - Ray Sources Based on Compton Scattering in Laser Electron Storage Ring // *PAST. Series: Nuclear Physics Investigation.* 2002, v.40, p.72-74.
3. V.E. Ivashchenko, I.M. Karnaukhov, N.V. Kovalyova, A.A. Shcherbakov, A.Yu. Zelinsky. Characteristics of synchrotron radiation of storage ring NESTOR and its applications // *PAST. Series: Nuclear Physics Investigation.* 2004, v.44, p. 139-141.
4. J. Murphy. *Synchrotron Light Source*, Data Book, BNL-4233 1989.
5. J. Schwinger// *Phys. Rev.* 1946, v.70, p. 798-799.
6. U. Arp. Influence of the Vertical Emittance on the Calculability of the Synchrotron Ultraviolet Radiation Facility // *Journal of Research of the National Institute of Standards and Technology.* 2002, v.107, p.419-423.
7. A. Hofmann.Characteristics of Synchrotron Radiation *CAS CERN 98-04:* 1998, p.1-30.
8. I.S. Guk, P.I. Gladkih. *Experimental research of angular and polarized of characteristics of synchrotron radiation of relativistic electron beam:* Preprint KIPT 83-13, 1983, p.4-8 (in Russian).
9. I.S. Guk, A.N. Savchenko. *About possibility of use of the synchrotron radiation of the storage ring $N-100$ KIPT AS USSR for absolute measurements in a range 500-2500Å :* Preprint KIPT 77-37, 1977, p.8-12 (in Russian).
10. I.S. Guk, N.I. Mocheshchnikov. *Status and prospects of development of works on use of the synchrotron radiation of the storage ring N-100:* Preprint KIPT 80-3, 1980, p.15-17 (in Russian).
11. Materials of international working conference "Synchrotron source UINR: prospects of researches" // *UINR.* Dubna , Russia, 1999 (in Russian).

СИНХРОТРОННОЕ ИЗЛУЧЕНИЕ ИЗ УСТАНОВКИ НЕСТОР

И.М. Карнаухов, Н.В. Москалец, А.А. Щербаков

Приведены основные характеристики синхротронного излучения генератора рентгеновского излучения НЕСТОР – нового электронного накопительного кольца с энергией электронов от 40 до 225 МэВ и с периметром 15.418 м.

СИНХРОТРОННЕ ВИПРОМІНЮВАННЯ З УСТАНОВКИ НЕСТОР

І.М. Карнаухов, Н.В. Москалецъ, О.О. Щербаков

Приведено основні характеристики синхротронного випромінювання генератора рентгеновского випромінювання НЕСТОР – нового нагромаджувача електронів з енергією від 40 до 225 МеВ та з периметром 15.418 м.