THE OPERATION MODES OF KHARKOV X-RAY GENERATOR BASED ON COMPTON SCATTERING NESTOR

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Abstract

The results of theoretical and numerical considerations of linear Compton scattering are used to evaluate characteristics of X-rays produced by collision between a low emittance electron beam and intensive laser light in an X-ray generator NESTOR of NSC KIPT. Two main generation modes have been under consideration at preliminary NESTOR design. There are the operation mode for medicine 33.4 keV X-rays production using 43 Mev electron beam and Nd:YAG laser beam and higher energy X-rays production mode providing X-rays with energy up to 900 keV with 225 MeV electron beam and Nd:YAG laser beam. It was supposed to use an optical cavity for laser beam accumulation of about 2.6 m long and an interaction angle of about 3^0 in both operation modes. A few more operation modes provide possibility to expand operation range of NESTOR. Using interaction angle 10^0 and 150^0 along with optical resonator of 42 cm long and the second mode of laser light it is possible to produce X-rays in energy range from a few keV till 1.5 MeV. The intensity and spectral brightness of the X-rays is expected to be $\sim 10^{13}$ phot/s and $\sim 10^{13}$ phot/s/mm^2/mrad^2/0.1%BW respectively.

INTRODUCTION

X-ray generators based on Compton scattering (CS) may become inexpensive prevailing sources of the intensive X-rays because their operation energy is much less than operation energy of synchrotron radiation sources. The main applications of such generators are medical studies, biological ones and science of materials over X-ray energy range from several keV up to several hundreds keV. Laser-electron storage ring NESTOR is under construction now at NSC KIPT [1]. This work is supported with SfP NATO Grant #977982. NESTOR is compact electron storage ring with circumference of about 15 m and operation energy range over 40 - 225 MeV. It is supposed that injection in the ring will be carried out from linac and maximum energy of injected beam will be of 60 MeV. The X-ray generation will be produced trough CS due to electron beam interaction with intense laser beam accumulated in an optical cavity. In the initial variant of optical system it was proposed to use long optical cavity with length equal to semi-circumference, interaction angle equal to zero and single interacting electron bunch [1]. Later on variant with shorter optical cavity (2.58 m), interaction angle equal to 2.86^0 and three interacting bunches was considered. Today, it seems to us, that variant with optical cavity 0.43 m long is more feasible, first of all, for the reasons of requirements to keep the geometrical parameters of the resonator. Besides, it is possible in short resonator to produce smaller optical beam waist. Simultaneously, scattered beam intensity decreasing can be compensated with increasing of interacting electron bunch number. It is supposed that laser optical system has to provide laser flash energy equal to 1 mJ. Due to lattice with controlled momentum compaction factor the energy acceptance of storage ring is very large and it allows us to use the operation modes with steady-state parameters of electron beam. The intensity of X-rays in such operation modes is very stable that is very important for some researches.

In this paper the computation parameters of X-rays are presented. All dependencies were obtained by electron beam dynamics simulation involving both intrabeam scattering (IBS) and CS.

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OPERATION MODE FOR ANGIOGRAPHY STUDIES

Under CS of a laser photon on a relativistic electron the energy of the scattered X-ray is determined by expression [3]:

$$\varepsilon_\gamma = \frac{1+\beta\cos\varphi}{1-\beta\cos\phi}\varepsilon_{las},$$

where ε_γ is the scattered quanta energy, ε_{las} is the laser photon energy, φ is the collision angle ($\varphi = 0$ corresponds to head-on collision), ϕ is the angle between vectors of electron and X-ray velocities, $\beta = v/c$ is the ratio of electron and light velocities. One can easily change the energy of scattered photons by changing or electron energy (β), or collision angle (φ), or observation angle (ϕ).

In order to provide X-ray generation over wide energy range we intend to use two optical cavities with collision angles $\varphi_1 = 10°$ and $\varphi_2 = 150°$ (Fig.1).

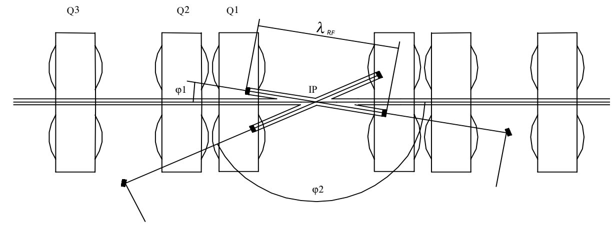

Figure 1. Arrangement of the equipment at interaction point (IP) drift. Collision angles $\varphi_1 = 10°$ and $\varphi_2 = 150°$, Q are the quadrupole lenses.

Angiography studies require X-rays with photon energy $\varepsilon_{ph} \approx 33$ keV. Such X-rays are generated under head-on collision of neodymium laser photons $\varepsilon_{las} = 1.16$ eV and electron beam with energy $E_0 \approx 43$ MeV. We are going to use for these experiments optical cavity crossing electron beam orbit under angle $\varphi_1 = 10°$. Unfortunately, the IBS strongly disturbs electron beam motion at such low energy and as a result the beam emitance quickly grows that causes the decreasing of the CS intensity. For example, the dependencies of the transversal and longitudinal emittances on time after injection in NESTOR lattice are presented in Fig.2. Operation mode at steady-state electron beam size is practically impossible because of low intensity of CS. Our simulations show that under realizable parameters of storage ring and laser system the value of Compton beam intensity does not exceed 10^{11} phot/s.

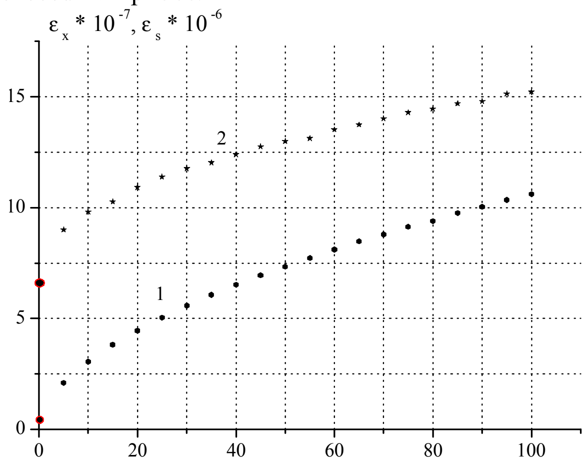

Figure 2. Horizontal ε_x (1) and longitudinal ε_s (2) emittances vs. time. Electron beam energy $E_0 = 43$ MeV, coupling coefficient $\kappa = 0.05$, stored current of electron bunch $I_{stor} = 10$ mA. Emittances of injected beam are $\varepsilon_{xinj} = 1*10^{-7}$, $\varepsilon_{sinj} = 6*10^{-6}$

In these calculations we assumed, that parameters of linac-injector are following:

– bunch charge $q_b = 0.5$ nC (corresponds to stored current of electron bunch $I_{stor} = 10$ mA);

– normalized transversal emittances $\varepsilon_x = \varepsilon_z = 8.5*10^{-6}$;

– bunch energy spread and length are $\delta = 0.3$ % and $\sigma_s = 2$ mm, accordingly.

During simulation interval because of IBS transversal emittance becomes ten times as large than initial one, longitudinal emittance becomes three times as large. In these conditions the intensity of CS quickly decreases that is shown in Fig. 3. One can see that during simulation interval the intensity of Compton beam becomes one-third of its initial value. The average intensities during simulation interval and within 10 ms period just after injection are approximately equal to $1.2*10^{12}$ phot /s and $2*10^{12}$ phot /s. In order to achieve high average long-term intensity of Compton beam we need injector with pulse repetition $f_{rep} \geq 10$ Hz.

The simulated spectrum of Compton radiation within 4π-solid angle for above described conditions is presented in Fig. 4. The spectral brightness under laser beam size $\sigma_{las} = 40$ μ is approximately equal to $5*10^{12}$ phot / (s*mrad ^{2}*mm^2*0.1%BW) and such brightness allows to carry out angiography studies.

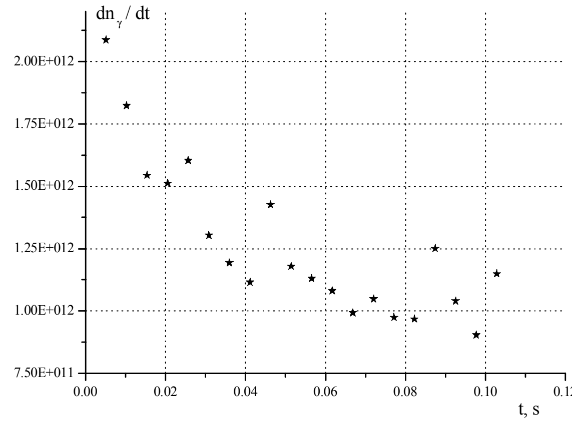

Figure 3. Compton beam intensity vs time. Electron beam energy $E_0 = 43$ MeV, bunch stored current $I_{stor} = 10$ mA, bunch number $n_b = 18$, stacked laser flash energy $w_{las} = 1$ mJ, collision angle $\varphi = 10°$, laser beam size $\sigma_{las} = 40$ μ.

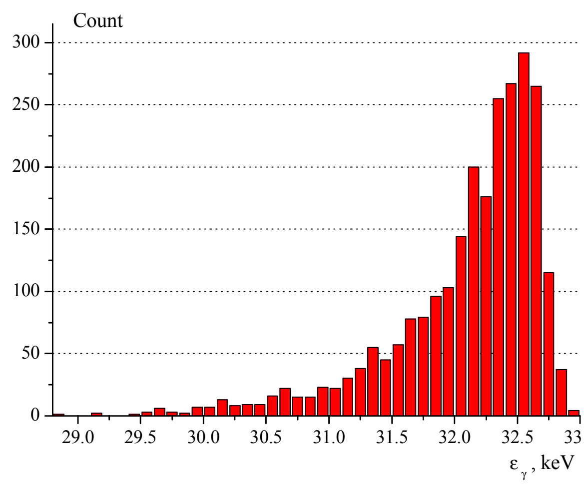

Figure 4. Spectrum of scattered photons within 1 mrad collimation angle. Electron beam energy $E_0 = 43$ MeV, collision angle $\varphi = 10°$.

BIOLOGICAL STUDIES

The most biological studies require X-rays with photon energy over range $5 \text{ keV} < \varepsilon_\gamma < 16 \text{ keV}$ and long-term stability of Compton beam intensity is very important for some of them. At head-on collision we need to use electron beam with energies over range $18 \text{ MeV} < E_0 < 30 \text{ MeV}$ in order to generate such X-rays. The steady-state operation mode of the storage ring with intensive electron beam is practically impossible at such small energies because of IBS. To meet the requirements of the biological studies we intend to use CS under collision angle $\varphi = 150°$. In this condition we need the energy of electron beam over range $70 \text{ MeV} < E_0 < 120 \text{ MeV}$. Of course, X-ray intensity at such collision angle will be much less than the one at small collision angle. Nevertheless, this intensity quite meets the requirements of the biological experiments. Besides, X-ray intensity will be very stable because we intend to use electron beam with steady-state parameters (at electron beam energy about of 100 MeV IBS-effect appears low).

The collimated spectrum of the photons for biological studies with maximal energy $\varepsilon_{\gamma max} \approx 6.7$ keV (electron beam energy $E_0 = 75$ MeV, collision angle $\varphi = 150°$) is presented in Fig. 5. Total Compton beam intensity within 4π-solid angle is approximately equal to $n_\gamma \approx 10^{11}$ phot/ s, number of photons within collimation angle $\alpha_{col} = 1$ mrad is $n_{\gamma col} \approx 2.5*10^9$ phot/ s, spectrum width is approximately 10%, number of photons within 0.1%BW at maximal photon energy is $n_{\gamma BW} \approx 2.3*10^8$ / s. Under laser beam waist $\sigma_{las} = 40\ \mu$ the spectral brightness is $B \approx 2*10^{11}$ phot/ (s* mrad ^{2}*mm^2* 0.1 % BW).

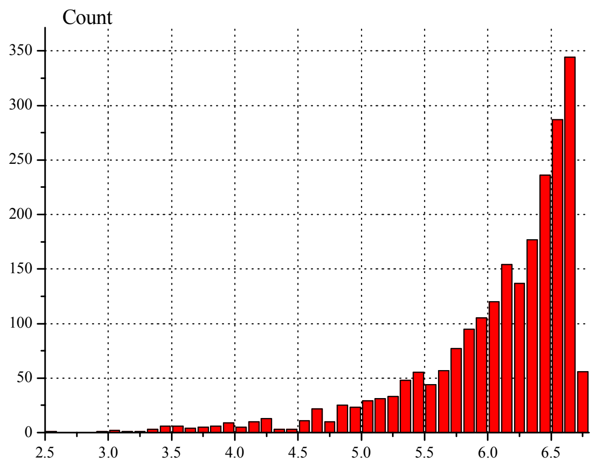

Figure 5. Scattered photons spectrum within collimation angle $\alpha_{col} = 1$ mrad. Electron beam energy $E_0 = 75$ MeV, collision angle $\varphi = 150°$.

EXPERIMENTS WITH HARD X-RAYS

In order to generate hard γ-quanta we intend to use 10°-collision of laser photons and high-energy electron beam with steady-state parameters. The total Compton beam intensity at maximal operation energy of the storage ring $E_{0max} = 225$ MeV is shown in Fig.6. Maximal γ-quanta energy is $\varepsilon_{\gamma max} \approx 900$ keV ($\varepsilon_{las} = 1.164$ eV). Insignificant decreasing of the scattered beam intensity is caused by energy spread increasing and electron bunches lengthening under Compton scattering. By means of the "green laser" ($\varepsilon_{las} = 2.328$ eV) we will be able to obtain 1.8 MeV γ-quanta energy. Such γ-quanta, for example, may be used for neutron generation in beryllium target.

SUMMARY

X-ray source NESTOR designing at NSC KIPT may be used for medical and biological studies, science of materials etc. X-rays over energy range $6\ \text{keV} \le \varepsilon_\gamma \le 900\ \text{keV}$ with long-term stable intensity up to 10^{13} phot /s can be generated under realizable parameters of the injector, storage ring and laser system. Maximum allowed Compton beam intensity limited by energy acceptance of the storage ring is approximately 10^{15} phot /s over all energy range. The main characteristics of NESTOR operation modes and produced X-ray are summarized in Table 1.

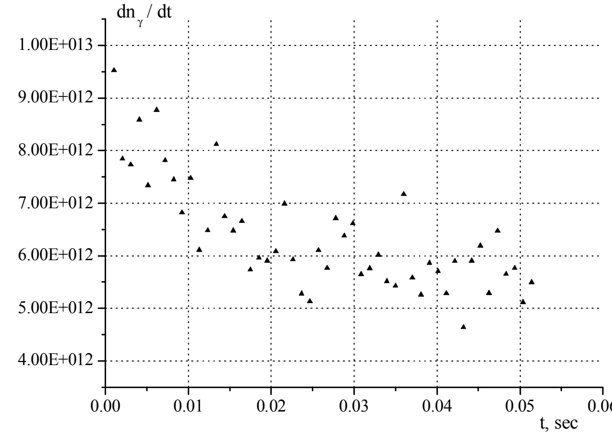

Figure 6. Compton beam intensity. Electron beam energy $E_0 = 225$ MeV, stored bunch current $I_{stor} = 10$ mA, number of electron bunches $n_b = 18$, stacked laser flash energy $w_{las} = 1$ mJ, collision angle $\varphi = 10°$.

Table 1. The main characteristics of NESTOR X-rays.

	Angiography	Biology	Hard X-ray
Interaction angle, Deg	10	150	10
Electron beam energy, MeV	43	70-120	60-225
X-ray energy, keV	33	5-16	900
Average X-ray intensity, phot/(s*mrad)	$2*10^{12}$	10^{11}	10^{12}-10^{13}
Spectral brightness, phot/(s mrad ^{2} mm ^{2} 0.1%BW)	$5*10^{12}$	$2*10^{11}$	$5*10^{12}$-$5*10^{13}$

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