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BEAM DYNAMICS INVESTIGATION FOR A NEW PROJECT OF COMPTON BACK SCATTERING PHOTON SOURCE AT NRNU MEPhI*

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Abstract

The activities on physical models design of a compact monochromatic radiation source in the X-ray range based on inverse Compton scattering are started at NRNU MEPhI. There are comparison of two schemes of the photon source here: one of them is considered to be based on linac with variable energy of 20-60 MeV only and the other one is considered as accelerator complex where linac is supposed to be used as injector to medium size storage ring (energy up to 60 MeV). Preliminary results of linac structures and storage ring design as well as electron dynamics simulation are discussed.

INTRODUCTION

Photons of 5-30 keV and flux of about 10^{10} - 10^{12} γ/s are used for materials science (design of new materials, diagnostics of nanostructures at the atomic level), research of nano - and biosystems (dynamic processes in living cells), medicine (phase-contrast imaging, dual-energy digital subtraction angiography) and pharmacology (development of new drugs), physics and chemistry of fast-flowing processes.

There are a few ways of 5-30 keV photon production (for instance, by means of a synchrotron, FEL, channeling radiation, coherent bremsstrahlung, Cherenkov's radiation, photon scattering by relativistic electron beams).

This project aims to development of a compact system for generating radiation in a next-generation light undulator in the photon energy range of 5-30 keV for ring and linear sources based on inverse Compton scattering.

The principle of a Compton source is based on X-ray pulses production by Compton back scattering of intense laser pulses (λ_{las}~μm) on an electron bunch with the energy of order of tens of MeV [1, 2]. Compact photon sources based on Compton back scattering make possible a wide-range of researches accessible and feasible in a laboratory-size environment. It is a way to overcome the shortage of synchrotron light sources and the small flux from traditional X-ray tubes.

Main difficulties on the way of achievement the required characteristics of generated photons are laser power limitation because of laser nonlinear effects appearance, noncoherence of the laser radiation, short time of interaction between accelerated electron bunch and laser photons, divergences and nonzero energy spreads of electron bunch and the laser photons.

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A number of facilities based on inverse Compton scattering effect are under design or operation today: MuCLS [3], LyCLS [4], ThomX [5], ODU CLS [6], SLEGS [7], SPARC_LAB [8], LUCX [9], LESR [10], Daresbury Compton Backscattering X-ray Source [11].

Compton light source is planned to be built on the NRNU MEPhI site. Two operating modes of the of compact light source are proposed: the storage ring Compton source design and the linac-based Compact-XFEL.

STORGE RING

In order to generate 5-30 keV X-rays in light ondulator it is suggested that compact storage synchrotron will be used with top-up injection from normal conducting S-band linac with tuneable energy in the range of 20-60 MeV.

The use of a storage ring provides the following advantages: high intensity of the generated photon flux, high brightness, electron beam energy tuning in a wide range, high degree of monochromaticity and coherence of the generated photons.

In order to get horizontal rms beam size at interaction point (IP) with laser photons of 30 μm for electron horizontal emittance $\varepsilon_{x,rms}$ of 100 nm the horizontal beta-function value should be equal to 30 cm in accordance with

$$\beta_x = \sigma^2_{x,\mathrm{rms}} \big/ \varepsilon_{x,\mathrm{rms}}.$$

The same value should have the vertical beta-function at IP. Dispersion function D_x should have a zero value at IP to minimize e-bunch size because

$$\sigma^2_{x,\mathrm{rms}} = \beta_x \varepsilon_{x,\mathrm{rms}} + D_x^2 \left[\left(p - p_0 \right) / p_0 \right],$$

where $\sigma_{x,rms}$ – horizontal rms beam size, β_x – horizontal beta-function, p – momentum of electron, p_0 – equilibrium momentum.

Furthermore, the length of storage ring straight section should be of 1.5 m to increase interaction efficiency between electron bunch and laser photons head-on collision as well as feasibility of laser positioning. The first linear version of the suggested synchrotron magnetic lattice is presented in Fig. 1. Storage ring circumference is 10.6 m. The quadrupole gradients were calculated numerically by means of AT [12] to satisfy requirements above. Figure 2 shows obtained optic functions. From Fig. 2 it is seen that β_x is 16.5 cm and β_y is 19.4 cm at IP. Momentum

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compactification factor is equal to 0.0671 at 60 MeV, frequency is 4.1 MHz, betatron horizontal and vertical tunes are 3.545 and 4.931 correspondingly. Also it was estimated dynamic aperture (DA) and momentum acceptance (MA) values (Figs. 3 and 4). DA is equal to 1 mm which is sufficient value for 30 µm beam-size. MA is equal to 0.2% for harmonic cavity RF voltage amplitude of 300 kV.

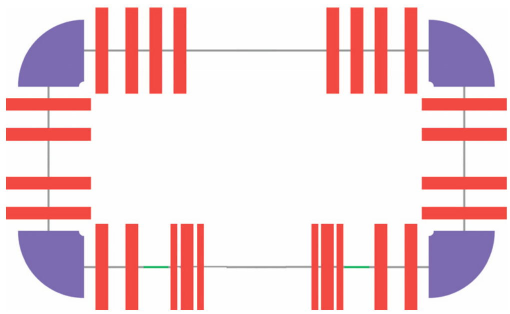

Figure 1: Basic magnet lattice of storage ring.

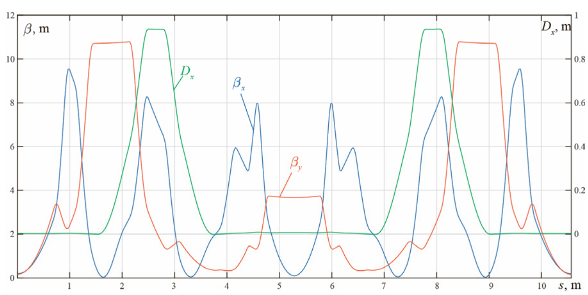

Figure 2: Twiss functions and dispersion.

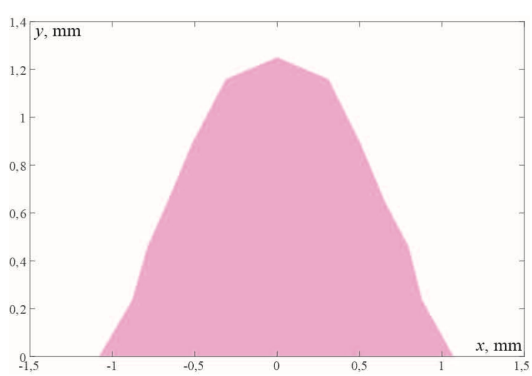

Figure 3: Dynamic aperture (for 1000 turns).

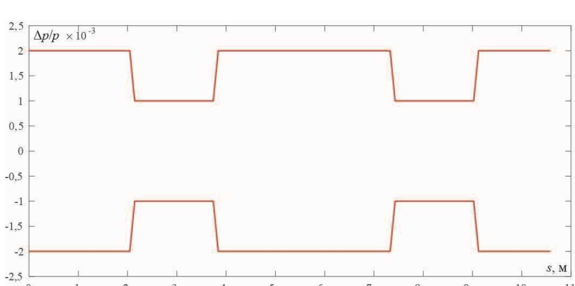

Figure 4: Momentum acceptance (U_{rf} = 300 kV).

Sextupoles will be arranged in the dispersion function maximum to correct chromaticities, but it will lead decrease DA value. It is supposed that single electron bunch lifetime will be of order of tens of ms.

LINAC DESIGN

It is proposed that the linac will be used for both light source operating mode: for an injection of a single bunch into compact storage ring and as a driver of bunch trains for Compact light source. The linac will consist of two sections (see Fig. 5). The first one is a photogun for production of the 0.1-1.0 nC and 1 ps or shorter electrons bunch. The second ("regular") one will accelerate the bunch up to maximal energy ~60 MeV. Note, that final energy is planned to be variable in the wide range (20-60 MeV).

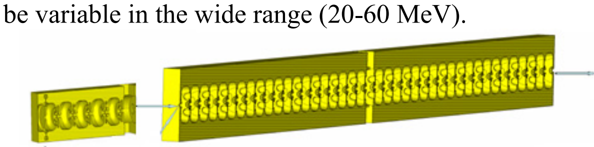

Figure 5: The general view of the linac for Compton source.

A choice of the accelerating cells optimal number and the RF-field gradient is base problem for the photogun. From the one hand, higher gradients give us possible to have simpler and shorter accelerating structure with the reduced influence of the Coulomb field in the near-cathode region. From the other hand, the decrease of the gradient leads to the narrow energy spectrum (see Table 1) and reduction of the necessary RF power. We propose to use 5.5-cell RF photogun for the light source [13].

Table 1: Bunch Energy and Spectrum vs Photogun Cell's Number and RF Field Amplitude

Cells	***E*, kV/cm**	φ_{inj}	W_{max}, **MeV**	$\Delta W/W$, **%**
3.5	600	2.0	6.2	1.8
5.5	600	2.7	8.1	0.9
5.5	700	2.8	8.2	1.2

Two options of the linac second section (operating frequency 2.8 GHz) were considered. The first one was the conventional SLAC-type 3-m-length traveling wave structure. The second one was biperiodic accelerating structure (BAS) with the accelerating gradient of 400 kV/cm and the length of 2.2 m. The second option gives 3-4 times lower final energy spread.

The beam dynamics simulation was carried out by using BEAMDULAC-BL code. This code was developed at MEPhI to study the beam dynamics taking into account both beam loading effect and Coulomb field simultaneously [14-17]. The results of the simulation are presented in the Fig. 6. From Fig. 6 one can see the phase portrait of the accelerated bunch with charge of 300 pC and its energy spectrum. The output energy is equal to 57.3 MeV, output

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energy spectrum is > ±0,1 % (for 4RMS). Note that the simulated value of the output transverse emittance is about 3 nm rad.

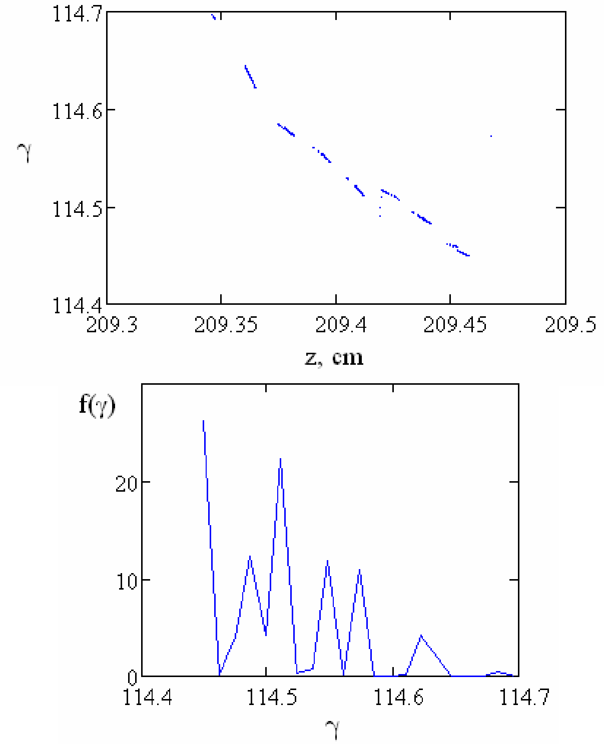

Figure 6: The beam dynamics simulation results for the linac: output bunch phase space (top) and energy spectrum (bottom).

CONCLUSION

Current activities on physical models design of a compact monochromatic radiation source in the x-ray range based on inverse Compton scattering are presented. A circumference of the storage ring is supposed to be about 11 m for one of the suggested operating mode. The total linac length is about of 2.8 m. This linac can be used not only as injector for the ring, but in the second operating mode that is linac-based Compact-XFEL.

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