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A PROJECT FOR A COMPTON PHOTON SOURCE AT THE SKIF SYNCHROTRON FACILITY

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Abstract

SKIF is a synchrotron radiation facility under construction in Novosibirsk, Russia. Its main storage ring has unique parameters, including an electron beam energy of 3 GeV, a beam current of up to 0.4 A, and a horizontal beam emittance of 75 pm · rad. These parameters make it suitable for creating a highly efficient high-energy photon source using Compton backscattering (inverse Compton scattering) of infrared, ultraviolet, and visible laser radiation. Using modern high-power lasers, it is possible to achieve Compton photons with energies hundreds-MeV range and rates up to 300 MHz. Additionally, higher Compton photon energies (up to 2.6 GeV) can be generated by reflecting synchrotron radiation towards the electron beam. A preferred method for photon monochromatization is tagging photons by their recoil electrons. The discussed Compton source can be used for photonuclear processes such as photofission and the production of π, η, Δ at nuclei, as well as for other applications such as nonlinear QED and calibration of electromagnetic detectors.

SKIF SYNCHROTRON RADIATION FACILITY

The Siberian Circular Photon Source SKIF [1] is a synchrotron radiation facility of "4+" generation currently under construction in Novosibirsk, Russian Federation. Its parameters (see Table 1) make it possible to create a high-quality source of Compton photons.

Table 1: Some Parameters of SKIF Synchrotron Facility

Energy	3.0 GeV
Perimeter	475.14 m
Electron beam current	400 mA
Horizontal emittance	75 pm · rad
Revolution frequency	629.63 kHz
Number of bunches	567
Time between bunches	2.8 ns (84 cm)

PROPERTIES OF COMPTON BACKSCATTERING

Compton backscattering is an interaction between a relativistic electron and a head-on, low-energy photon (see Fig. 1). The photon gains the maximum energy when it is

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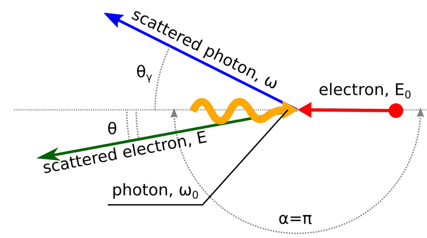

Figure 1: Scheme of Compton backscattering.

scattered back ($\theta = 0$):

$$\omega_{\max} = \frac{E_0 \kappa}{1+\kappa} \overset{\kappa \ll 1,\ \alpha=\pi}{\approx} 4\gamma^2 \omega_0, \quad \kappa = \frac{4\omega_0 E_0}{m^2}. \tag{1}$$

The scattered photon energy depends on the scattering angle (see notations in Fig. 1):

$$\omega(\theta) = \frac{\omega_{\max}}{1+(\theta/\theta_c)^2}, \quad \theta_c = \frac{m}{E_0}\sqrt{1+\kappa} \overset{\kappa \ll 1}{\approx} \frac{1}{\gamma}. \tag{2}$$

Electron recoil energy:

$$E = E_0 - \omega, \quad E_{\min} = E_0 - \omega_{\max} = \frac{E_0}{1+\kappa}. \tag{3}$$

The differential cross-section of Compton backscattering and the polarization of scattered photons are shown in Fig. 2.

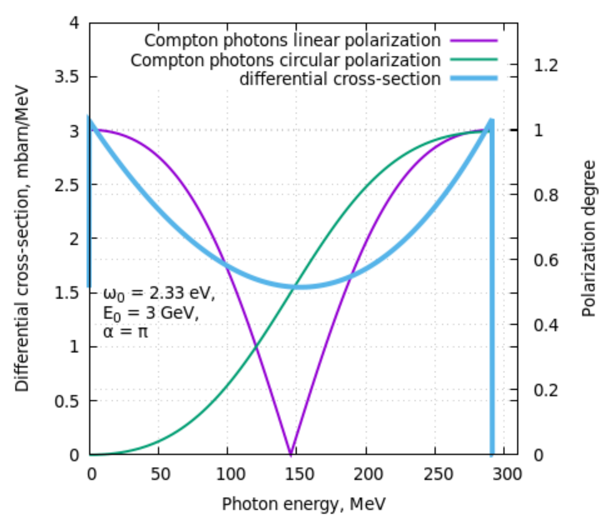

Figure 2: Differential cross-section and polarization degree of Compton backscattering.

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When Compton backscattering occurs in a magnetic field its differential cross-section becomes undulating due to the interference of gamma-quanta along the circular electron orbit [2]. This is illustrated in Fig. 3, which shows the most notable case that can occur at the SKIF facility.

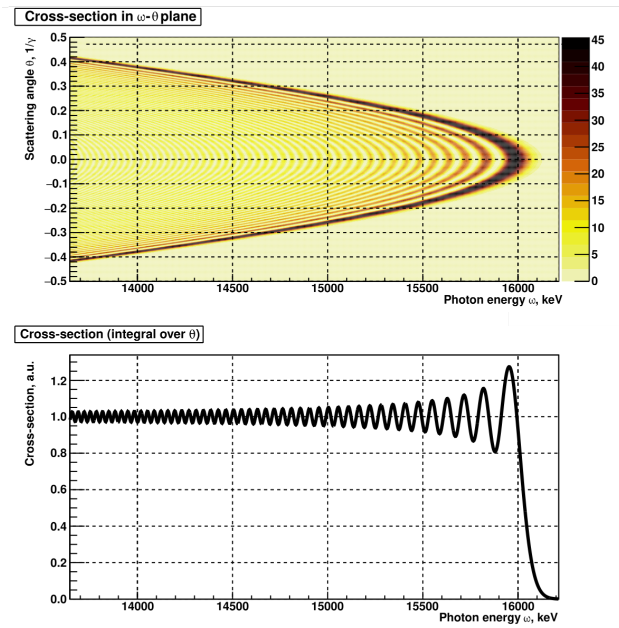

Figure 3: The differential cross-section of Compton backscattering (in relative units of measurement) in a magnetic field [2]: $B = 0.56\,\mathrm{T}$, $E_0 = 3\,\mathrm{GeV}$, $\Omega_0 = 0.117\,\mathrm{eV}$.

CONCEPT

The structure of the proposed Compton source at the SKIF facility is shown in Fig. 4. Laser radiation with one of the several possible wavelengths passes through a focusing and polarizing optical system. It is then inserted into the storage ring vacuum chamber with a pair of mirrors. The first mirror is movable and motorized and is located outside the vacuum chamber, while the second one is a part of the vacuum chamber itself. The laser beam interacts head-on with the electron beam. The most preferred interaction region is located within one of the soft-field dipoles of the supercell (BDA1 type). Compton photons that are scattered from the interaction point exit through the same laser input mirror (see the detailed scheme of the interaction region in Fig. 5), passing through collimators (if necessary) into the experimental hall. Scattered particles can separated from charged particles using veto counters and/or magnets. The experimental hall contains targets and detectors for hadrons, nuclei, photons for specific experiments. The remaining, unreacted, Compton photons beam goes to an electromagnetic calorimeter (for calibration purposes) and veto counters (to remove charged particles).

Recoil electrons are deflected by the bending magnets outside the equilibrium beam and can be detected by a tagging system built into the storage ring. A flange with a transparent window should be installed in the vacuum chamber opposite to the laser input unit. This can be used for diagnostic purposes, as well as the possible implementation of an optical resonator inside the vacuum chamber and other applications.

Continuous wave or nanosecond-pulsed lasers with a jitter of ~0.1 ns should be used. In the first case, Compton gamma-ray bursts would occur at a rate of $3.57 \cdot 10^8$ photons per second, which exceeds the throughput of most detectors. In the case of a pulsed laser, $\sim 10^8$ Compton gamma-ray bursts per second could be processed by the detectors. Lasers wavelengths could be selected among the most efficient lasing media: I, II and IV harmonics of Nd:YAG/Nd:YLF and CO_2. Tunable lasers could also be used, but only if an optical cavity is installed inside the storage ring, which could significantly increase the optical intensity.

PHOTON SPECTRA AND RATES

Figure 6 shows the calculated Compton photon rates for CW laser with a power of 1 W and a waist size of 50 µm at the interaction point ($\lambda = 527\,\mathrm{nm}$). The figure also shows some energies related to nuclear physics. The total, full-spectrum photon rate is ~30 MHz. Lasers with other wavelengths could be focused to achieve the same rate per watt.

LIMITATIONS AND FEATURES

The main purpose of the storage ring is to generate synchrotron radiation. Therefore, the proposed Compton source is limited by the following factors.

The electron beam energy cannot be changed, so the maximum energy of Compton photons (see Eq. (1)) can only be adjusted only by changing the laser wavelength. This can be done by using many powerful single-wavelength lasers or tunable lasers with a high-Q optical cavity inside the vacuum chamber. Alternatively, the energy of Compton photons can be measured by tagging by recoil electrons, using Eq. (3).

Significant deterioration of lifetime and electron beam quality is not permitted at the synchrotron radiation facility. Therefore, recoil electrons with an energy loss of up to 78 MeV (2.6 % of the beam energy; particularly, all recoil electrons from CO_2 laser) remain in a storage ring and may cause emittance deterioration. At the same time, the rate of Compton photons is limited by the injection system: up to $\sim 4 \cdot 10^8\ \gamma/\mathrm{s}$, if the recoil electrons leave the equilibrium beam (most of the recoil electrons from Nd:YAG/Nd:YLF lasers).

Some parameters of the SKIF lead to some useful features of the proposed Compton source. The bunch repetition rate is 357 MHz, so, considering the maximum allowed rate, the Compton photon multiplicity is less than 1. In this case the tagging system works with low pile-up. Such a high bunch repetition rate requires the use of either continuous wave or specialized high-rate pulsed lasers.

The SKIF electron beam has a low emittance and a low angular and coordinate spread. The closest analogues are MAX-IV and Sirius storage rings. This leads to efficient collimation of Compton quanta for monochromatization

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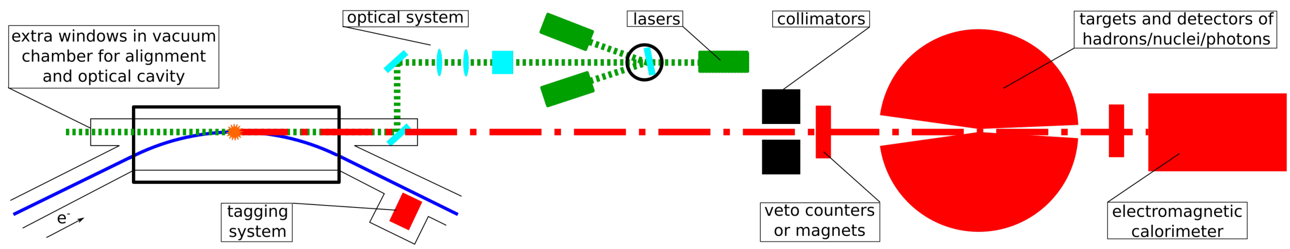

Figure 4: Layout of the proposed SKIF Compton source.

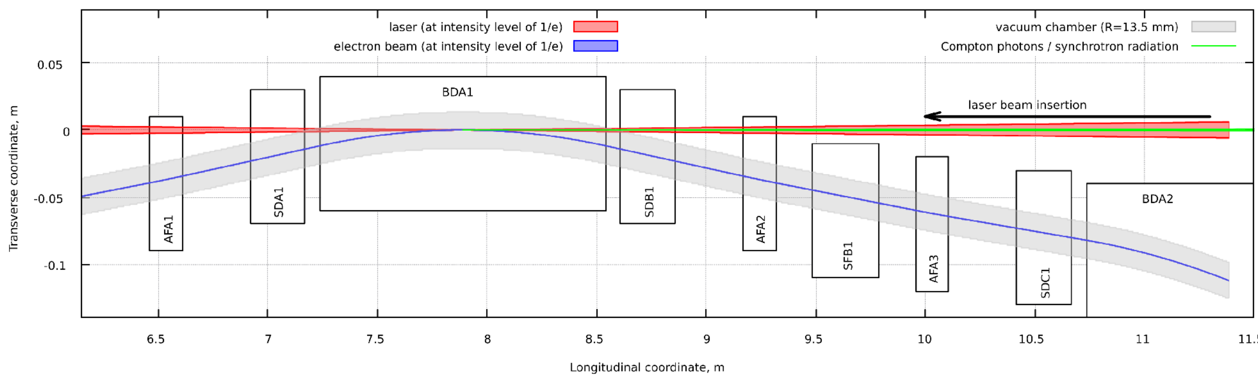

Figure 5: Layout of the interaction region.

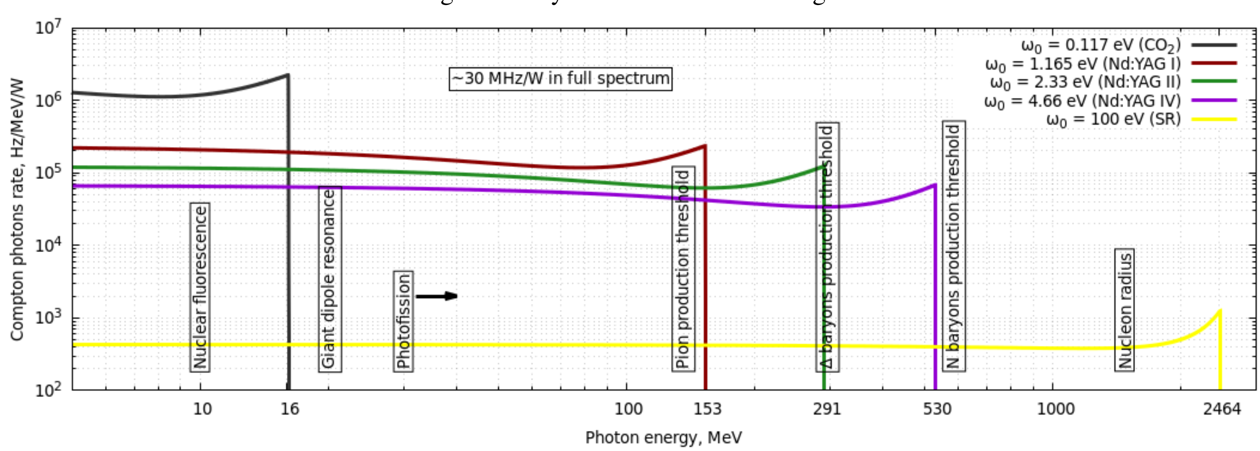

Figure 6: Compton photons spectra.

and polarization selection. Additionally, the tagging system achieves high energy resolution. Probably, with a twisted laser beam, twisted Compton photons can be generated at the maximum energy.

TAGGING SYSTEM

Considering vacuum chamber radius of 13.5 mm, two tagging systems are required: one for photons with energies up to 400 MeV (Compton photons from a Nd:YAG/Nd:YLF green laser); and another for photons with energies up to 600 MeV, (Compton photons from UV lasers).

The two parts of the tagging system can be placed in the same periodic cell of the storage ring. One part is 1.2 m to 2.4 m from the interaction point and the other is 4.6 m to 5.8 m from the interaction point, see Fig. 7. The calculated photon energy resolution is from 0.6 % to 0.8 % of the beam energy, which corresponds to a photon energy resolution of ~2 MeV. Two Si/GaAs strip single-coordinate movable detectors located inside the vacuum chamber will be suitable for this application. The detector strip pitch could be 50 µm. Taking into account the proposed rates, the photon multiplicity is <0.5, which means that the tagging systems will operate almost without pile-up (if the detector is able to operate at 357 MHz).

OBTAINING VERY HIGH-ENERGY PHOTONS

Using the reflected backwards synchrotron radiation from the electron beam, it is possible to obtain Compton photons with ω_{max} = 2464 MeV, as shown in Fig. 8. According to the article [3], a focusing mirror operating at a wavelength of 12.4 nm (100 eV) with a bandwidth ±2.5 % can be manufactured. Its reflection coefficient is 0.7, so calculated Compton photon rate is approximately 600 kHz (with a scattering cross-section of 29 % the Thompson cross-section).

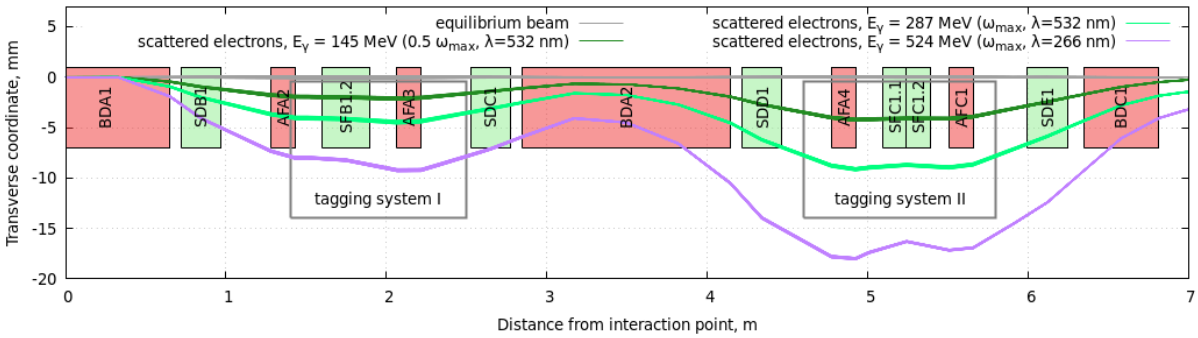

Figure 7: Tagging systems and recoil electrons trajectories.

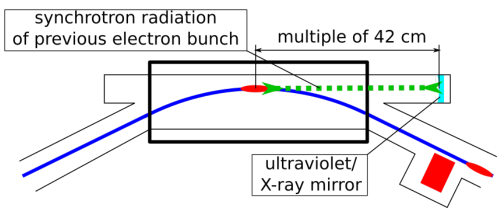

Figure 8: A method to obtain very high-energy Compton photons.

POSSIBLE EXPERIMENTS

The "low-energy" range (units–tens MeV), with experiments in nuclear fluorescence, pygmy resonances and the problem of "bypassed" nuclei, etc. is almost inaccessible for the proposed facility. The reason is that the beam energy is fixed and the tagging system is not able to operate with such low-energy recoil electrons.

At the higher energies the following promising experiments could be conducted:

- Photonuclear reactions in "mid-energy" range (hundreds of MeV): nucleus photofission, production of hypernuclei, pions, hyperons, etc., as well as nonlinear QED effects. The tagging system could be used.
- Energy scale calibration and measurement of energy resolution of electromagnetic detectors.
- Possibly, gamma tomography and the production of radioisotopes for nuclear medicine.

Also some methodical experiments could be conducted:

- Optical cavity inside the storage ring vacuum chamber to increase radiation power.
- Using synchrotron radiation as a source of initial photons.
- Obtaining twisted Compton photons using twisted laser beams.

If IR tunable lasers with sufficient power or with optical cavity are used, monochromatization can also be achieved through gamma beam collimation for "low-energy" experiments.

We propose to conduct the following first experiments, which were previously conducted in 1980s–1990s at the VEPP-4 collider:

- Actinides nuclei photofission with 100–500 MeV photons [4]. The fissility of ^{237}Np has been found to be 60 % greater than that of ^{238}U, which is defined as the sum of pion photoproduction on all nucleons of the nucleus. This issue has not yet been fully resolved [5].
- Nonlinear QED experiments: Delbrück scattering [6] and photon splitting [7] in atomic fields.

With the unique parameters of the SKIF these experiments can be conducted with excellent efficiency and precision.

CONCLUSION

- A draft design for a Compton source in a SKIF storage ring has been proposed.
- Individual components of the facility are being developed.
- Experts in photonuclear physics and detector technology are needed.
- Further ideas for the physical program are required.

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