FOCUSING LATTICES OF COMPTON GAMMA – RINGS *

E. Bulyak, P. Gladkikh, NSC KIPT, Kharkov, Ukraine
K. Moenig, DESY, Zeuthen, Germany & LAL, Orsay, France
T. Omori, J. Urakawa, KEK, Ibaraki, Japan
F. Zimmermann, CERN, Geneva, Switzerland

Abstract

The results of the joint work of physicists from the CERN, KEK, LAL, DESY, and KIPT for the design of a Compton ring dedicated to the generation of intense polarized γ–beam are presented in this report. Such a beam is generated via Compton scattering of circularly polarized laser beam off a high-energy electron beam stored in a Compton ring. The γ–beam is used for the generation of an intense polarized positron beam for linear a collider. This scheme was approved as an alternative to the ILC undulator scheme last August at the Snowmass–2005 workshop. This report discusses the primary design principles of the Compton ring lattice and it presents electron beam-dynamics simulations for the preliminary lattice of a CO_2 Compton ring at energy of 4.1 GeV in the presence of intense Compton scattering.

INTRODUCTION

The base scheme for obtaining the intense polarized positron beam is the scheme with undulator [1]. The electron beam with energy $\sim 100 \ldots 150$ GeV passing through spiral undulator generates polarized γ–quanta with maximal energy $15 \ldots 30$ MeV. One can obtain such γ–quanta at much lower energy of electron beam using Compton scattering of the polarized laser beam on relativistic electron beam. For example, at head–on collisions with the photons of a CO_2 laser we need an electron energy of about 4.1 GeV in order to obtain scattered γ–quanta with a maximal energy 30 MeV or an electron energy equal to 1.3 GeV using a YAG laser. Successful experiments of laser–electron γ–beam generation were already carried out at the KEK/ATF storage ring [2].

BASE PRINCIPLES OF DESIGN OF RING LATTICE

Several serious problems arise at lattice design. The first and the main problem is associated with the large energy spread of the electron beam caused by intense Compton scattering. The total energy spread δ_{tot} caused by both synchrotron radiation and Compton scattering is determined by expression

$$\delta_{tot} = \sqrt{\frac{\Delta E_{SR}}{\Delta E_{tot}}\delta_{SR}^2 + \frac{\Delta E_{CS}}{\Delta E_{tot}}\delta_{CS}^2} \,,$$

where $\delta_{SR}, \Delta E_{SR}$ and $\delta_{CS}, \Delta E_{CS}$ are the partial energy spreads and energy losses due to synchrotron radiation and Compton scattering, correspondingly, $\Delta E_{tot} = \Delta E_{SR} + \Delta E_{CS}$.

Usually partial energy spread caused by Compton scattering is much greater than the one due to synchrotron radiation and determined by the following expression [3]

$$\delta_{CS} = \sqrt{\frac{7}{10}\gamma\frac{\varepsilon_{las}}{\varepsilon_0}} \,,$$

where γ is the Lorentz factor, $\varepsilon_{las}, \varepsilon_0$ are the energy of laser photon and the rest electron energy. For example, at an electron beam energy of 1.3 GeV and YAG laser ($\varepsilon_{las} = 1.16$ eV) $\delta_{CS} \approx 6$ %.

Positrons will be generated during short pulses with pulse duration about of 100 microseconds and repetition rate about of 100 Hz. The total number of generated positrons is about of 10^{14} per second. At a photoproduction efficiency equal to 0.014 the Compton ring must produce about of 10^{16} gamma–quanta per second. In these conditions each electron scatters about of 0.35 gamma–quantum per turn at an electron bunch population corresponding to the bunch charge of 10 nC. The corresponding energy losses caused by Compton scattering are equal to 2.7 MeV and these energy losses are greater than those caused by synchrotron radiation at reasonable bending field. If the scattering goes on continuously the steady–state energy spread in the electron beam is about 3 % and 6 % for Compton rings with CO_2 and YAG lasers, respectively.

It is evident that keeping the long term stable motion of such electron beam is questionable. Firstly, we need a very large energy acceptance

$$\sigma_{rf} > 4 \ldots 5\delta_{tot} \,,$$

secondly, we have to correct the chromaticity up to a high order

$$\Delta Q = \frac{\partial Q}{\partial \delta}\delta_{tot} + \frac{\partial^2 Q}{\partial \delta^2}\delta_{tot}^2 + \frac{\partial^3 Q}{\partial \delta^3}\delta_{tot}^2 + \ldots$$

and, thirdly, we have to suppress the dispersion functions up to high order at the interaction points. The horizontal offset at an interaction point as a function of the relative momentum deviation is written as

$$\Delta x = \eta_1\delta + \eta_2\delta^2 + \eta_3\delta^3 + \ldots \,,$$

where η_n is the dispersion function of n–th order. If the higher-order dispersion functions are not suppressed, the

* Work supported by ELAN/CARE collaboration

intensity of the scattering will decrease because of an increase in the horizontal electron-beam size during scattering.

Taking into account the above considerations, we propose to switch on the pulse laser only for a short time for Compton beam generation and injection of the produced positrons into the damping ring. Then the electron beam is damped due to synchrotron radiation until the following positrons train is generated.

It is difficult to obtain the analytical evaluation of the parameters of both electron and photon beams in such a quasi–stationary operation mode because the problem needs to be solved self–consistently. The intense Compton scattering changes the parameters of an electron beam, which in turn leads to a change in the scattering intensity. We have developed a code for simulation of electron–laser beam interaction in "idealized" Compton ring. In this code the ring lattice is represented in terms of a few fundamental parameters such as the betatron tunes, the amplitude functions at the interaction points, the RF–voltage, the linear momentum compaction factor and those of higher order etc.

In Fig. 1 one can see the dependence on time of energy spread during several Compton cycles as the example of such simulation. Each cycle consists of a generation period and a period of damping of both the electron beam in the Compton ring and the positron beam in the damping ring.

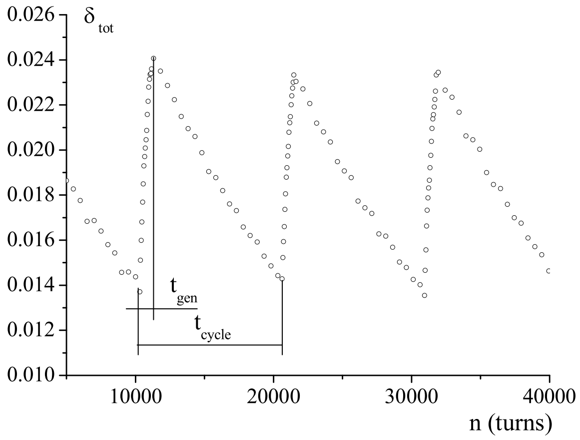

Figure 1: Total energy spread of electron beam during several generation cycles.

The other problem of lattice design is obtaining of the electron beam with a size less than the corresponding size of the laser beam (approximately 25 microns for transversal size and 1 mm for longitudinal one) at the interaction point. At small collision angle the number of scattered photons per electron and per turn is determined by the expression

$$n_\gamma \approx \frac{n_{ph}\sigma}{\sqrt{z_e^2 + z_{ph}^2}\sqrt{(x_e^2 + x_{ph}^2) + (s_e^2 + s_{ph}^2)\varphi^2/4}}\,,$$

where x_e, z_e, x_{ph}, z_{ph} are the transversal sizes of an electron and laser beams, s_e, s_{ph} are the longitudinal ones, φ is the collision angle, σ is the cross–section of the Compton scattering, n_{ph} is the photon number in laser bunches over all interaction points (here and from now on we assume that the electron and laser beams collide in the horizontal plane).

Obtaining of the transverse size mentioned above is not a complicated problem at reasonable electron beam emittance and amplitude functions at the interaction point. It is much more difficult to obtain the required longitudinal size. As it is well known, the electron bunch length is determined by the expression

$$s_e = \frac{\alpha_1 c}{\Omega_s}\delta\,,$$

where α_1 is the linear momentum compaction factor, Ω_s is the synchrotron frequency, c is the speed of light. For example, to obtain the bunch length less than 1 mm in storage ring with synchrotron frequency $\Omega_s = 5\,$kHz (i.e., a synchrotron tune of 0.01 for a storage ring with circumference $C = 600\,$m) we have to provide α_1 less than 1.66×10^{-6} at the energy spread $\delta_{tot} = 0.01$. Even at such small momentum compaction factor electrons with pulse deviation greater than 1% will not scatter the laser photons efficiently. As the simulation of Compton scattering shows the γ–beam intensity decreases quickly during gamma generation because of electron bunch lengthening.

To weaken this effect we have proposed to use some features of the synchrotron motion at very low momentum compaction factors. In this case we have to take into account the quadratic and higher order terms in orbit lengthening

$$\frac{\Delta C}{C} = \alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + \dots\,,$$

where α_n are the linear, quadratic, cubic etc. momentum compaction factors. It is well known that quadratic momentum compaction factor must be as small as possible because it limits the energy acceptance. The phase trajectories in plane of synchrotron motion at small linear, quadratic and cubic momentum compaction factors can assume a shape as shown in Fig. 2

In this figure the phase trajectory of synchrotron motion for base version of ILC Compton Ring with CO_2 laser is shown. If we displace the initial electron beam position to the vertical branch using RF phase manipulation by the time of γ–generation, we can get a long period of synchronization of the electron and photon beams because the longitudinal position of electron only weakly depends on the momentum deviation on this branch.

An alternative approach for maximizing the overlap of laser beam and electron beam is the following. Very roughly we can represent the synchrotron motion at intense Compton scattering as the motion on spiral (Fig. 3) In this figure the red lines determine the placement of the laser flash. In the above presented method the synchrotron frequency must be as small as possible. In this figure one can

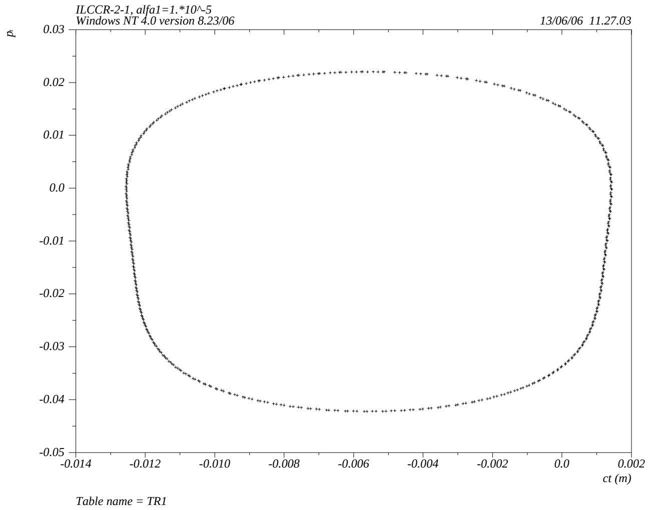

Figure 2: Phase trajectory of synchrotron motion. Electron energy $E_0 = 4.1$ GeV, linear momentum compaction factor $\alpha_1 = 10^{-5}$ (MAD simulation).

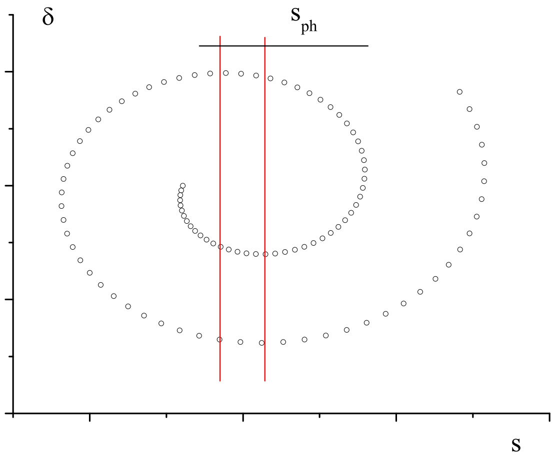

Figure 3: "Averaged" synchrotron motion at intense Compton scattering.

see that the scattering intensity can be increased if electron comes into the synchronism with the laser flash during the synchrotron motion more than once. Thus, synchrotron frequency must be as large as possible in this method. For example, we can increase the synchrotron frequency by increasing both the RF frequency and the RF voltage.

The above considerations lead us to the conclusion that lattice design must allow us:

- to decrease the linear momentum compaction factor down to the level of 10^{-6};
- to obtain a large energy acceptance;
- to correct the chromaticity up to high order;
- to suppress the dispersion functions up to high order at interaction points.

To meet these requirements we have proposed the Compton ring lattice with controlled momentum compaction factors [4]. Its layout is presented in Fig. 4.

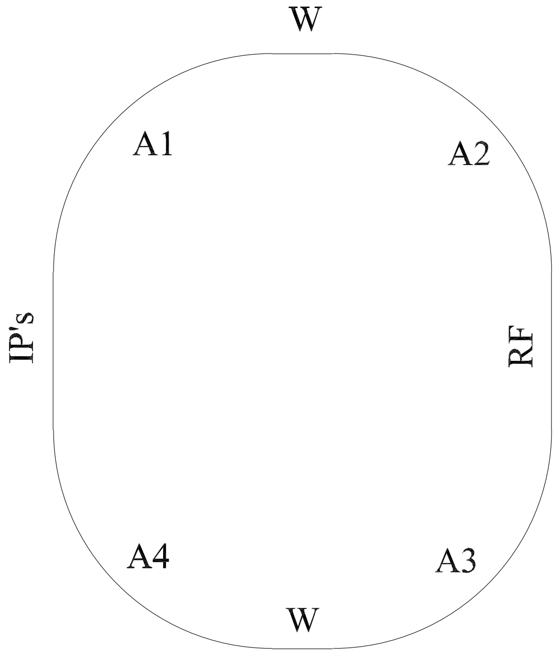

Figure 4: Layout of Compton ring.

The ring is of the racetrack type with four long straight sections:

- section with length about of 63 m comprising 30 IP's. The horizontal and the vertical amplitude functions at IP's are 1.5 m and 3.5 m, correspondingly;
- section with length about of 63 m comprising RF accelerating structures and the injection system;
- two sections with lengths approximately equal to 25 m for wigglers. The wiggler field strength is equal to 2.3 T at the electron energy $E_0 = 4.1$ GeV. Such wigglers provide the energy losses which are equal to those in the bending magnets. The usage of wigglers allows us to reduce the natural electron beam emittance down to 1.8 nm at the electron energy $E_0 = 4.1$ GeV.

In every long–straight section the focusing structure is of FODO type. The focusing structure of the arcs consists of four–bending cells with two dispersion–free drifts and a drift section with nonzero first order dispersion. Each arc consists of 20 dipole magnets. Thus there are a total of 80 bending magnets in the ring. The amplitude and dispersion functions of a four-dipole cell are presented in Figs. 5 and 6.

In Fig. 6 one can see that the dispersion function becomes negative for part of the orbit in the bending magnets. This makes it possible to obtain zero or even nega-

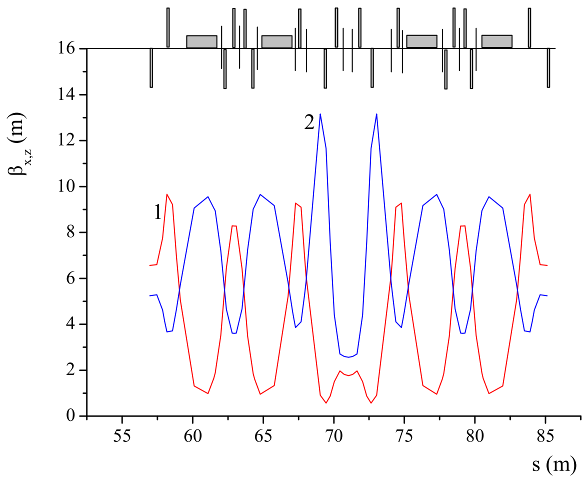

Figure 5: Horizontal (1) and vertical (2) amplitude functions of a four–bending section.

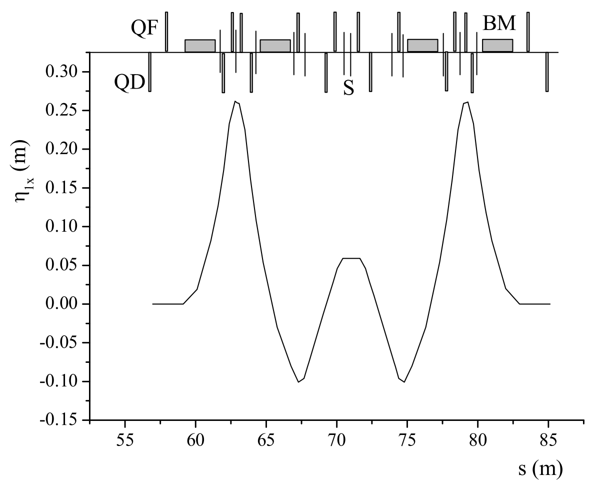

Figure 6: First order dispersion function of a four–bending section. BM are bending's, QF, QD quadrupoles, S sextupoles.

tive value of α_1. At operation mode with low momentum compaction factor the horizontal emittance is $\epsilon_x = 1.8\,\mathrm{nm}$ (at $\alpha_1 = 10^{-5}$ and electron energy $E_0 = 4.1\,\mathrm{GeV}$). At these conditions and at the coupling coefficient equaling 0.02 the bunch sizes at IP are 50 microns and 11 microns in horizontal and vertical planes, correspondingly. It is worth mentioning that transition from a conventional operation mode with "large" compaction to the low–compaction one doubles the emittance.

Number of sextupoles in dispersion section of the arc cells allow for an efficient suppression of the chromatic aberrations at the IP's and for minimizing the second order momentum compaction factor. Phase-space trajectories in the two transverse planes for a particle with large momentum deviation as well as the second-order dispersion function over half of the ring are presented in Figs. 7, 8, and 9, respectively.

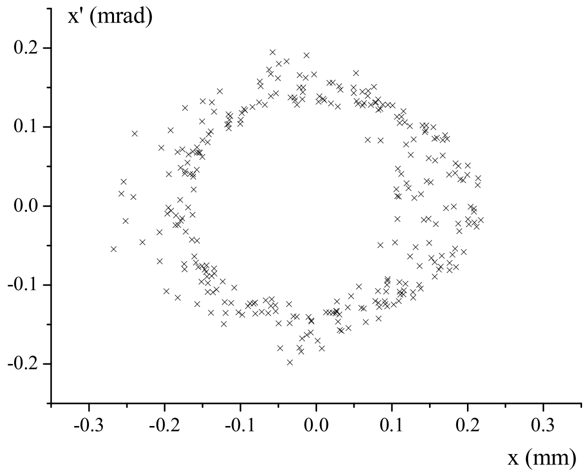

Figure 7: Phase trajectory in horizontal plane. Initial particle coordinates are $x = z = 0.1\,\mathrm{mm}$, $x' = z' = 0, \delta_{max} = 3\,\%$.

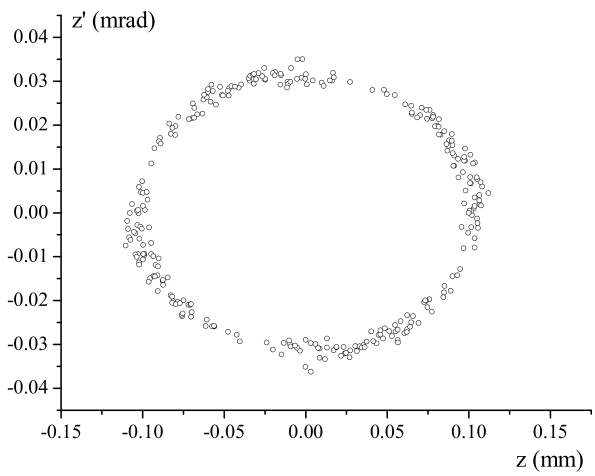

Figure 8: Phase trajectory in vertical plane. Initial particle coordinates are $x = z = 0.1\,\mathrm{mm}$, $x' = z' = 0, \delta_{max} = 3\,\%$.

Electron bunch population is equal to 6.2×10^{10}. The required averaged intensity of a γ–bunch is equal to 1.8×10^{10} per bunch and per turn, that is equivalent to the averaged yield of 0.3 gamma's per one electron and per turn during generation time. Preliminary simulation of the Compton scattering in the lattice considered here shows the possibility of such intensity of radiation at the compaction factor α_1 equaling to 1×10^{-5} and number of generation turns equaling to 80.

The spectrum of γ–quanta within the collimation angle 0.1 mrad is presented in Fig. 10. Within the interval from

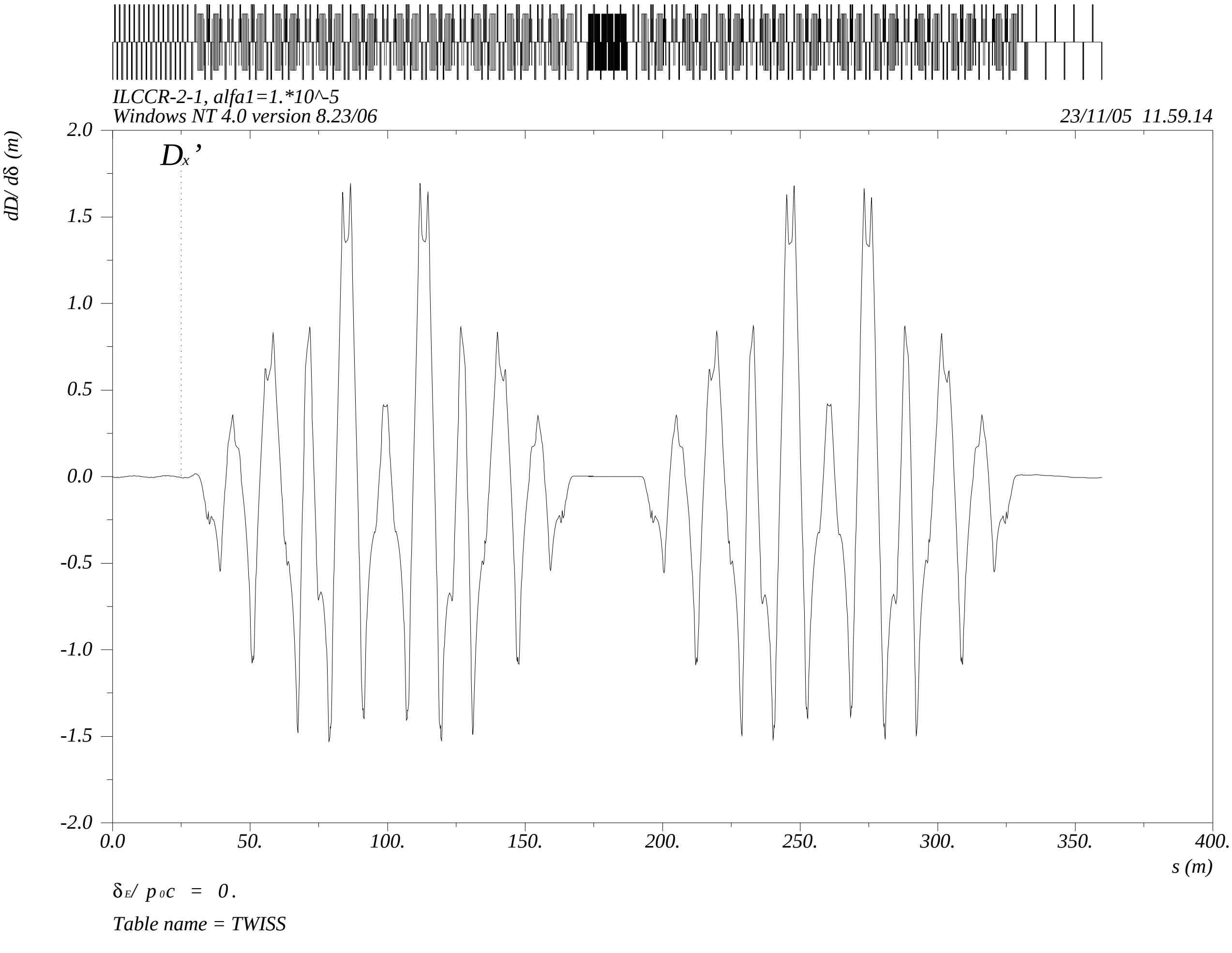

Figure 9: Second order dispersion over half of the ring.

23 to 30 MeV each electron scatters the required 15 γ–quanta during generation time.

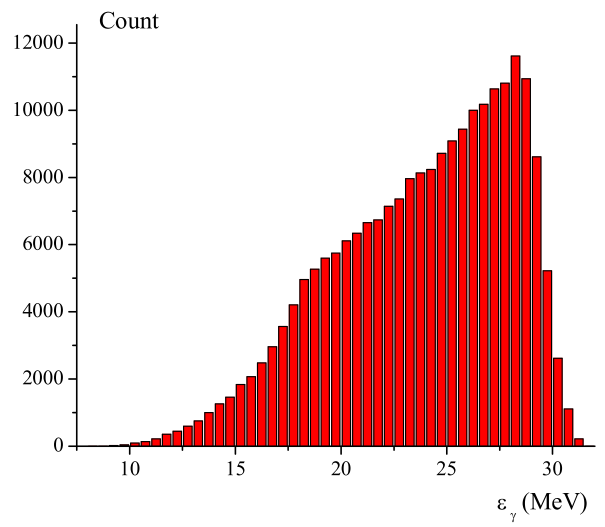

Figure 10: Spectrum of γ–beam within collimation angle 0.1 mrad. Electron energy $E_0 = 4.1$ GeV, number of particles is 1000.

In the case when both colliding beams are parallel and the energy spread of an electron beam equals to zero the gamma-beam spectrum is determined by collimation angle and has clear-cut edges while the spectrum in Fig. 10 has fuzzy edges. Fuzziness of the high energy edge is determined by the energy spread of electron beam, fuzziness of the low energy edge is associated with the electron beam divergence. The long low-energy "tail" in Fig. 10 shows, that the electron beam divergence is comparable with characteristic gamma–beam divergence equaling to $1/\gamma$.

The gamma-beam intensity of the full train obtained with RF phase manipulation is presented in Fig. 11. The initial coordinates of the electron beam in the synchrotron phase space are a longitudinal offset of 0.012 m (that corresponds to 10 degrees) and zero momentum deviation.

If we choose RF frequency three times larger, we can get the same 15 gamma–quanta per electron during 120 turns of generation without RF phase manipulation, as it is shown in Fig. 12. There are three peaks in this dependence. The first peak corresponds to the beginning of both generation time and synchrotron oscillation. The second peak corresponds to half synchrotron period and the third peak corresponds to the end of synchrotron oscillation. As one can see in this figure the synchrotron period corresponds to approximately 100 turns.

The main parameters of the CO_2 Compton ring are presented in Table 1.

BEAM INSTABILITIES

The beam may be unstable in the ring with very low momentum compactions. That is why we suggest the following operation mode of the Compton ring.

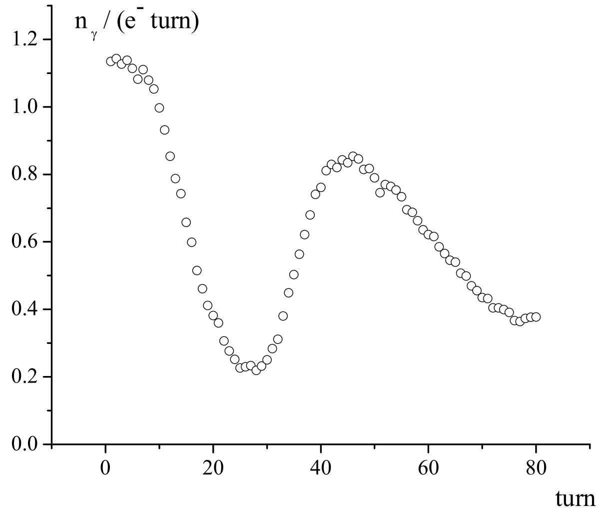

Figure 11: Gamma beam intensity in train vs. turn number. $f_{rf} = 650$ MHz, initial coordinates $s = 0.012$ m (corresponds to 10 degrees), $\delta_{ini} = 0$.

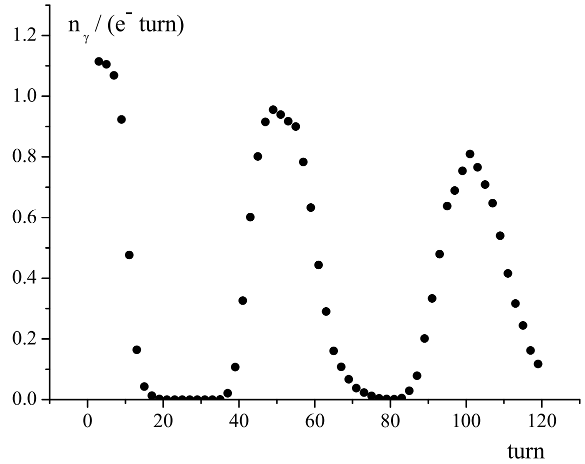

Figure 12: Gamma beam intensity in train vs. turn number at $f_{rf} = 1950$ MHz. Initial electron beam coordinates $s = 0.$, $\delta_{ini} = 0$.

A minimal possible compaction factor that provides the stable operation is pre-set by tuning of quadrupole strengths in the arcs. Just before switching on the laser system, the weak pulse quadrupoles of the arc cells diminish the compaction down to the required level of order 10^{-6} or 10^{-5} during a short time period of about one turn. In this mode, the train of gamma-quanta is produced. At the beginning of the cooling period the momentum compaction increases back to the "stable" level. We expect that serious instabilities do not develop during the short interval of about 100 turns used for gamma generation, when the

Table 1: Main parameters of Compton ring

Parameter	**Value**
Electron energy, GeV	up to 5
Circumference, m	719.5
Harmonics number	1560
RF frequency, MHz	650 (1950)
RF voltage, MV	60
RF acceptance, %	≈ 7
Betatron tunes	53.17; 22.24
Momentum compaction factor	$0 \leq \alpha_1 \leq 2 \times 10^{-4}$
Chromaticity	-73.9; -49.4
Emittance at maximal energy	2.8×10^{-9}

momentum compaction is small. A possible placement of pulsed quadrupoles over an arc cell is presented in Fig. 13.

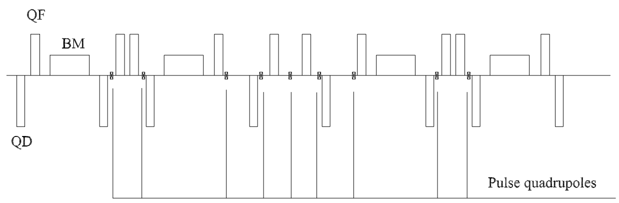

Figure 13: Distribution of pulsed quadrupoles over a Compton-ring arc cell. The pulsed quadrupoles are used for dynamically lowering the momentum compaction factor during periods of Compton scattering.

CONCLUSION

The preliminary design of the CO_2 Compton ring suggests the possibility of stable beam operation in such a ring at the intensity of Compton scattering required for polarized positron generation. The beam dynamics simulation including Compton scattering show zero particles losses during the gamma-beam generation.

The Compton ring with an electron beam energy equal to 1.3 GeV and neodymium laser is more preferable because of lower cost and the state of the art of neodymium laser technology. At the present time we are designing such YAG Compton rings for the ILC and CLIC projects.

REFERENCES

[1] A. Mihailichenko. Use of Undulators at High Energy to Produce Polarized Positrons and Electrons, SLAC-R-0502 (1997) 229.

[2] I. Sakai, T. Aoki, K. Dobashi, M. Fukuda, A. Higurashi, T. Hirose, T. Iimura, Y. Kurihara, T. Okugi, T. Omori, J. Urakawa, M. Washio and K. Yokoya. Production of high brightness gamma rays through backscattering of laser photons on high–energy electrons. Physical Review Special Topics–Accelerators and Beams, 6:091001, 2003.

[3] Z. Huang and R.D. Ruth. Laser–Electron Storage Ring. Phys. Rev. Lett. 80, 976 (1998).

[4] P. Gladkikh. Lattice and beam parameters of compact intense X–rays source based on Compton scattering. Physical Review Special Topics–Accelerators and Beams, 8:050702, 2005.