# POSSIBLE APPLICATIONS OF WAVE-BEAM INTERACTION FOR ENERGY MEASUREMENT AND OBTAINING OF POLARIZATION AT FCCee

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*Abstract*

Possibility to monitor beam energy in FCCee with an accuracy of $10^{-4}$ using Compton scattering on a waveguide wave is under consideration. Methods based on interaction of a beam with circularly polarized photons for obtaining beam polarization, proposed and theoretically substantiated in the past but not yet approved anywhere, are briefly discussed in regard to parameters of FCCee.

## INTRODUCTION

The aim of the work is an attempt to imagine some new possibilities which a beam-wave interaction can impart to the FCCee project development in regard to beam energy monitoring and obtaining of spin polarization.

One of them is an application of waveguide wave for a beam energy determination by the Compton scattering.

The precision beam energy calibration with an accuracy of $10^{-6}$ using the resonant depolarization technique will be applied at FCCee in the experiment of the Z mass measurement [1]. Such calibration procedures will be conducted periodically depending on the timing cycles of obtaining and utilization of beam polarization. The gained experience of the similar experiments (see, for example, [2]) shows an acute need to continuously monitor a beam energy in the intervals between these procedures with an accuracy of at least the order of a beam energy spread. The reason for this is a long-term instability of guide field and violations of a storage ring geometry due to temperature changes and tidal effects.

Compton Back Scattering (CBS) on a relativistic electron beam in a storage ring is applied now to monitor the beam energy with an accuracy of up to a fraction of the beam energy spread which makes diffuseness of the Compton spectrum edge. In the top quark experiments the Compton scattering may be considered as a main method for beam energy determination because of growing problems [1] with obtaining spin polarization at energies >100 GeV.

Accuracy of the VEPP-4M CBS monitor of beam energy with the working laser wavelength of 10 $\mu$m amounts $2.5 \times 10^{-5}$ at the beam energy spread of $3 \times 10^{-4}$ [2]. Question of possibility to apply a similar CBS monitor at 45-175 GeV FCCee turns on the issue of the use of significantly longer wavelengths of incident waves providing a limit of scattered photon energy of the order of 5 MeV which is feasible for detecting [3]. Taking into account such limitation we should take the wavelength $\lambda > 8$ mm. Such a problem definition looks like obvious but the corresponding possibility still has not been studied.

In the past the original proposals to obtain spin polarization in storage rings of the LEP energy range using laser waves were developed at Budker Institute [4, 5]. But no experiments have been performed to approve these proposals anywhere till now. We briefly discuss them in regard to the FCC project general parameters.

## WAVEGUIDE COMPTON MONITOR OF BEAM ENERGY

### *Compton Scattering Kinematics in Waveguide Mode*

According to the Compton kinematic scheme in Figure1 a momentum $k_2$ of a scattered photon is related to an analogous parameter before scattering ($k_1$) by the equation (the useful formulae on the Compton effect are presented in [6])

$$k_2 = \frac{k_1(1-\beta\cos\theta_1)}{1+\frac{k_1}{E}[1-\cos(\theta_2-\theta_1)]-\beta\cos\theta_2}, \qquad (1)$$

where $E = m\gamma$ and $\beta$ are the initial energy and velocity of an electron. When a microwave radiation with a frequency

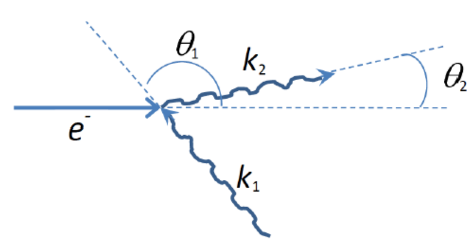


Figure 1: Kinematic scheme of Compton scattering.

$\omega = 2\pi c/\lambda$ induced in the FCC vacuum chamber propagates towards the beam one can observe the Compton Back Scattering of the corresponding photons. In the limit of very small wavelengths $\lambda << \lambda_c$ ($\lambda_c$ is a critical wavelength) the incident photons fly practically along an axis of the chamber-waveguide ($\theta_1 = \pi$) and energy of scattered photons equals to

$$\omega' \approx \frac{4\gamma^2\omega}{1+\gamma^2/\theta_2^2}, \qquad (2)$$

or $\omega' = 4\gamma^2\omega$ at $\theta_2 = 0$. This is valid for laser beam because of its high directedness. In the general case a geometric description of Compton scattering of waveguide waves undergoes change. The easiest way to consider this change is to use the Brillouin approach based on partial plane waves (see Figure 2). Direction of the partial waves are given by the angle

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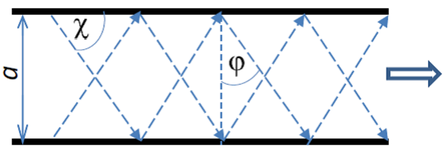


Figure 2: Geometry of partial waves in a plane waveguide.

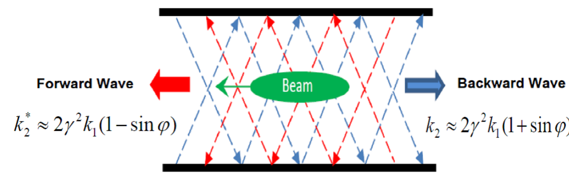


Figure 3: Scheme with the backward and forward waveguide waves.

$\chi = \chi_n$ (relative to the axis) or $\varphi = \varphi_n$ (relative to a normal to the axis) which take strictly determined values related to the type ($H_{m,q}$ or $E_{m,q}$) and the order ($n = \{m, q\}$) of the waveguide wave and corresponding critical wavelength ($\lambda_c = \lambda_c^{(n)}$):

$$\cos\chi = \sin\varphi = \frac{\lambda}{\Lambda} = \sqrt{1 - \frac{\lambda^2}{\lambda_c^2}} = \frac{c}{v_{ph}}, \quad (3)$$

$\Lambda = \lambda v_{ph}/c$ is a waveguide mode period; $v_{ph}$ , a phase velocity in a smooth waveguide, is larger than the light speed ($v_{ph} > c$). Scattering of backward partial waveguide waves at the incident angle $\varphi$ (see Figure 2.) yields the CBS Compton spectrum edge which is shifted down according to (1) ($k_1/E << 1$) as

$$k_2 \approx 2\gamma^2 k_1(1 + \sin\varphi). \quad (4)$$

Next, we use as a base example the wave in a round waveguide with the following parameters and features:

- $a = 4$, cm, the waveguide diameter;
- $\lambda = 5.5$ cm, the wavelength parameter of the plane waves with the frequency of 5.45 GHz;
- $\lambda_c = 3.41a/2 = 6.82$ cm, the critical wavelength for the lowest round waveguide mode - $H_{11}$;
- 5.24 cm is the critical wavelength of the next nearest mode - $E_{01}$ and, thus, the "mono-wave" condition $2.6a < 2\lambda < 3.41a$, meaning that only the lowest mode $H_{11}$ survives, is fulfilled - this is important for one-valuedness of the CBS spectrum edge determination;
- $\varphi = 36°$ so the collision angle $\theta_1 \neq 180°$ but 127°;
- CBS spectrum edge goes down regarding that in the "head on" case resulting in their ratio $k_2(\varphi)/k_2(\pi/2) = (1 + \sin\varphi)/2 = 0.795$.

Since the critical wavelength depends on the waveguide transverse size, the CBS spectrum edge also depends on it. From here one can conclude that the use of the Waveguide Compton CBS for monitoring of a beam energy with a reasonable accuracy of $10^{-4}$ is not possible without knowing the waveguide sizes of the same accuracy along the wave-beam interaction region.

## *Two Wave Scheme*

In this work we suggest to avoid the obstacle mentioned above using two waves instead of one - the backward ($\theta_1 = \pi/2 + \varphi$) and forward ($\theta_1 = \pi/2 - \varphi$) waves of the same frequency (Figure 3). The latter is excited at the opposite end of the waveguide section with respect to the backward wave (BW). The spectrum edge for the forward wave (FW) is given by a formula:

$$k_2^* \approx 2\gamma^2 k_1(1 - \sin\varphi). \quad (5)$$

Let us introduce the ratio $R = k_2/k_2^*$. Then combining (4) and (5) we find

$$\sin\varphi = \frac{R-1}{R+1}. \quad (6)$$

That disposes of difficulty to know exactly the waveguide sizes as the beam energy can be determined from

$$\gamma = \sqrt{\frac{k_2}{2k_1} \cdot \frac{(R+1)}{R}} = \sqrt{\frac{k_2 + k_2^*}{2k_1}}, \quad (7)$$

where $k_1$ is known with a good accuracy by the frequency of the GHz signal source; $k_2$ and $k_2^*$ are determined owing to measurement of the gamma quanta spectrum edges in the BW and FW cases using the same detector. For the base example with the $H_{11}$ wave parameters described above the ratio $R$ amounts

$$R = \frac{1 + \sin\varphi}{1 - \sin\varphi} = 2.69, \quad (8)$$

Sketch in Figure 4 shows a variant of the two wave scheme at FCCee basing on the straight sections where an interaction of FW and BW with the electron and positron beams occurs. The length of interaction can be limited with ceramic insertions in the vacuum chamber at the ends of sections.

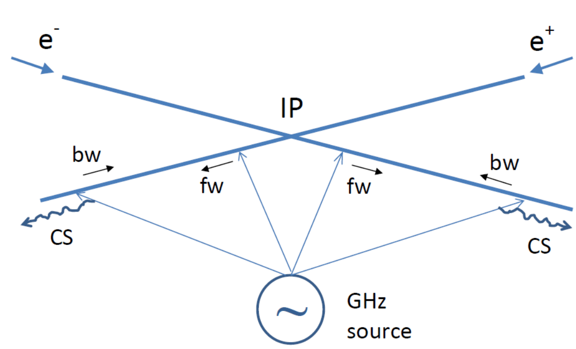


Figure 4: Scheme of organization of waveguide sections at FCCee with the Compton monitor on the backward and forward waveguide waves.



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### Monochromaticity and Effective Length of Interaction

Beam-wave interaction region scale is determined by the requirement on the extent of inmonochromaticity. This extent can be found from the uncertainty relation for a moving sinusoid bit which characterizes a monochromaticity of the wave train at the effective interaction length $L_i$:

$$\frac{\delta\lambda}{\lambda} = \frac{\lambda}{L_i} \quad (9)$$

The effective length $L_i$ depends on a number of the wave crests intersecting a particle during its motion in the wave. Hence we obtain for the backward wave

$$L_i = 2v_{ph}\frac{L}{\beta c}. \quad (10)$$

taking into account that the partial plane waves make a longer path in the waveguide of the length $L$ as compared with the light signal directed along the waveguide axis but in a free space. Factor "2" arises due to the fact that in a time of passage of the beam in the waveguide $T$ the counter wave train forms in a length corresponding to the time $2T$. As consequence the inmonochromaticity extent in the BW case equals to

$$\frac{\delta\lambda}{\lambda} = \frac{\lambda}{2L}\sin\varphi = \frac{\lambda}{2L}\sqrt{1-\frac{\lambda^2}{\lambda_c^2}}. \quad (11)$$

At the base example parameters and the length $L = 100$ m of a straight section occupied by the waveguide the inmonochromaticity of interaction is $\delta\lambda/\lambda = 1.6 \times 10^{-4}$.

At the same time the analogous quantity in the FW case is expressed through the effective length

$$L_i = \left(\frac{v_{ph}}{\beta c} - 1\right)\cdot L, \quad (12)$$

and then

$$\frac{\delta\lambda}{\lambda} = \frac{\lambda}{L}\frac{\sin\varphi}{(1-\sin\varphi)}. \quad (13)$$

This gives the FW inmonochromaticity $\delta\lambda/\lambda = 7.9 \times 10^{-4}$ at $L = 100$ m. Assuming that $\delta\lambda/\lambda = \delta k_2/k_2$ we find the error of the energy determination from (7)

$$\frac{\delta\gamma}{\gamma} = \frac{1}{2}\frac{(\delta\lambda/\lambda)_{FW} + (\delta\lambda/\lambda)_{BW}(1+\sin\varphi)(1-\sin\varphi)^{-1}}{[1+(1+\sin\varphi)(1-\sin\varphi)^{-1}]}$$

$$+\frac{1}{2}\frac{\delta k_1}{k_1} = 1.4 \times 10^{-4}$$

(we suppose $\delta k_1/k_1 << \delta k_2/k_2$).

### Relation of Scattering Angle and Monochromaticity Bandwidth

Let us define a monochromaticity bandwidth in the spectrum of scattered photons as a quantity equal to the inmonochromaticity extent determined above in the BW case:

$$\frac{\delta\omega_s}{\omega_s} = \frac{\delta\lambda}{\lambda} \sim 10^{-4}. \quad (14)$$

Scattered photons fly in a cone at small angles $\theta \sim 1/\gamma << 1$ in accordance with the differential cross section

$$\frac{d\sigma}{d\Omega} \approx \frac{r_e^2\gamma^2}{1+\gamma^2\theta^2}. \quad (15)$$

In the interval $0 < \theta < \theta_c$ a corresponding portion of the cross section amounts

$$d\sigma_c \approx 2\pi r_e^2\gamma^2\theta_c^2.$$

The relation between the scattering angle and the photon energy is found from (1):

$$\omega_s \approx \frac{2\gamma^2\omega(1+\sin\varphi)}{1+\theta^2\gamma^2}. \quad (16)$$

Combining (14) and (16) we obtain the characteristic angle of scattering in the interval of monochromaticity $\delta\omega_s/\omega_s \sim 10^{-4}$ ($\lambda_s = 2\pi c/\omega_s$):

$$\theta_c = \sqrt{\frac{\lambda_s}{L_i}} \sim 10^{-7}. \quad (17)$$

Corresponding portion of total cross section $d\sigma_c \approx 10^{-4}2\pi r_e^2 \sim 10^{-4}\sigma_T$ where $\sigma_T = (8/3)\pi r_e^2 = 6.6 \cdot 10^{-25}\text{cm}^2$ is the Thomson cross section.

In the presence of quads at the waveguide section a particle trajectory is variable in direction with characteristic angular spread $\sqrt{\mathcal{E}_x/\beta_x} \sim 10^{-5}$ (in the FCCee project $\mathcal{E}_x \sim 10$ nm, the horizontal beam emittance; $\beta_x \sim 100$ m), that is much larger than the characteristic scattering angle $\theta_c \sim 10^{-7}$. Therefore, a real interaction length is determined by a mean distance between the quads $L_q < L$ where the particles move straight [7]. Waveguide section should not contain quads. The section length $L = 100$ m can be acceptable since the beta function in FCCee may be of the same scale. Also one needs to provide a magnetic shield decreasing the Earth magnetic field inside a waveguide chamber down to level of $\sim 10^{-3}$ Gs with the aim to limit a rotation angle of the beam axis to $\theta_c$ .

### Estimate of CBS Photon Statistics

Number of photons scattered on a moving electron at an interaction length $l$ is given as

$$dN_s = \sigma_T \cdot n_i \cdot l \cdot (1+\cos\chi). \quad (18)$$

where $\chi$ is an angle of incidence of photons to a beam; $n_i \approx W/(Sc\hbar\omega)$ is a photon density expressed through a wave power $W$, a waveguide cross section $S$ and the photon energy $\hbar\omega$ ($\approx 2 \cdot 10^{-5}$ eV at $\lambda = 5.5$ cm). The resulting statistics of scattered photons will be as $\delta N_s \approx 5 \times 10^{-7}$ photons from a single electron and $dN_s = 5 \times 10^4$ photons from a single bunch per a single passage in the waveguide section for the base example parameters, $L = 100$m, a bunch population $N_e = 10^{11}$, the waveguide power $W = 100$ Watt.

To measure Compton spectrum one needs to shift down the number $dN_s$ to $dN_s \leq 1$ photon:

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- $W < 1$ Watt;
- $N_e \leq 10^9$ a bunch population;
- $dN_s = 1$ scattered photons/bunch/passage;
- $N_b = 10^3$ a number of bunches;
- $f_0 = 3$ kHz, a revolution frequency;
- $1 \times N_b \times f_0 = 3$ MHz, a total rate of the CBS photons;
- 300 Hz is a $10^{-4}$ portion of scattered photons in the interval $d\omega_s/\omega_s \sim 10^{-4}$ at the spectrum edge.

An injection can be organized to maintain, for instance, every tenth bunch with a $10^9$ population. It allows monitoring the particle energy during an acquisition of statistics in the experiments on colliding beams In this case the useful counting rate of the CBS photons will be 300 kHz.

### *Background Conditions*

Compton scattering on thermal radiation photons ($trp$) [8] can be a source of background for the Waveguide Compton beam energy monitor at FCCee. Let us base on the estimates made for LEP and experimentally approved. At $E = 50$ GeV and 300 K, the room temperature, the main parameters of the thermal radiation photons are as following: $n_{trp} = 5.45 \times 10^8$ cm$^{-3}$, the trp density; $\bar{\omega}_{trp} = 0.07$ eV, the characteristic $trp$ energy; $x = 4E\bar{\omega}_{trp}/m^2 = 0.055$, the interaction parameter; $xE = 2.75$ GeV, the scattered photon energy. The large energy loss $\Delta E/E = x = 5.5\%$ means that a knockout of electron from a beam is unavoidable. The corresponding beam lifetime makes up $\tau_{trp} = 92000\,\mathrm{s} \sim 10^5$ s. Applying these characteristics for the case of Waveguide Compton monitor at the 50 GeV FCCee ($N_e = 10^9$, $f_0 = 3$ kHz, $L = 100$ m) we obtain :

- $\delta N_{trp} = \frac{N_e}{\tau_{trp}} \frac{L}{c} = 0.003$ photons from a single bunch with $N_e = 10^9$ per a single passage;
- $\frac{\delta N_{trp}}{dt} = \delta N_{trp} \frac{N_b f_0}{10} \approx 1$ kHz a background counting rate due to trp when using an every tenth bunch for CBS monitoring.

The $trp$ background for the proposed conditions (1kHz) is much less than the rate of useful events (300 kHz). For comparison: the VEPP-4M CBS monitor yields 10 kHz taking $5 \times 10^6$ events in 10 min providing an accuracy $5 \times 10^{-5}$. According to the Telnov's calculation for LEP at energies $E \geq 50$ GeV the beam lifetime due to $trp$ and that due to Bremsstrahlung are of the same order at the typical average residual gas pressure $\sim 10^{-9}$ Torr. All this suggests that the eficiency of the Waveguide Compton monitor of beam energy at FCCee can be fairly high.

## LASER METHODS FOR OBTAINING BEAM POLARIZATION

In the framework of the FCCee project the polarized beams are needed, in particular, for precise measurement of the beam energy using the resonant depolrization technique in the experiment on Z- mass measurement. Sokolov-Ternov polarization time in the 80 km FCCee ring is very large: $\tau_0 \approx 150$ h at 45.6 GeV. It makes the task of obtaining polarization directly in Main Ring or in Injector Ring rather difficult. In [4, 5] two methods using interaction of beam with circularly polarized photons were proposed and theoretically substantiated to obtain polarization in e+e- storage rings in the cases when other methods are ineffective :

- "Soft Photons" ($\chi = 2\gamma\hbar\omega/m << 1$, $c = 1$) is based on multiple scattering of electrons in the wave field. There is no output of scattering particles from a beam. Principle role belongs to a special spin-orbital coupling created in the region if beam-wave interaction (IR), for instance, with a solenoid of a fixed field integral (11 kGs·m regardless the beam energy);
- "Hard Photons" ($\chi = 2\gamma\hbar\omega/m >> 1$) consists in dominating knock-out of electrons of one of helicity signs from a beam. It requires an organization of equilibrium longitudinal direction of polarization in the wave-beam interaction region.

The authors of [4, 5] noted that the usual quantum lasers can be applied in certain cases. In the long term wider possibilities would be realized using Free Electron Lasers.

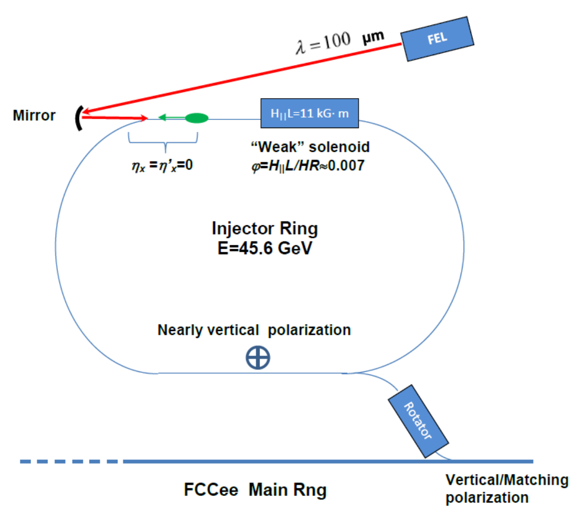


Figure 5: The possible variant of Soft Photon scheme for FCCee. At the interacion region the condition of zero dispersion ($\eta_x = \eta'_x = 0$) should be fulfilled to minimize an increase of transverse beam sizes.

The Soft Photon polarizing mechanism is based on indirect action of a field of radiation on a spin - through a perturbation of particle trajectory due to a change in energy. This is called the "spin-orbit coupling" and takes into account the effect of variation in a particle momentum on a precession axis $\vec{n}$. The variant of the Soft Photon scheme is shown in Figure 5. According to [4, 5] the scheme provides in IR the optimal spin-orbit coupling $\gamma\partial\vec{n}/\partial\gamma = \sqrt{10/7}\vec{\beta}$ and the direction of polarization axis transverse in regard to a particle velocity (the unit vector $\vec{\beta}$): $\vec{n} \cdot \vec{\beta} \approx 0$. It is assumed that polarization occurs at the spin precession frequency paramerer close to half integer values ($\nu = \gamma a \approx 103.5$ at $E = 45.6$ GeV). We have made the preliminary estimates for FCCee which show that Soft Photons using a 100 $\mu$m FEL with reasonable parameters can speed up notably the polarization process at 50 GeV. For instance, the polarization



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time can be made as $A = 26$ times lower than that due to synchrotron radiation in bending magnets. At the same time such a method fundamentally results in significant increase of the beam energy spread: by a factor of $\sqrt{1 + (63/110) \cdot A}$ times (= 4 at $A = 26$). In this relation the Soft Photons competes poorly with the usual method using a set of strong wigglers with a non-zero average cube of field which can provide a tenfold speed up of polarization doubling the energy spread [9]. Nevertheless, in contrast to the wiggler method, the Soft Photons allows polarization of a beam without noticeable energy consumption in the RF cavities. This follows from the fact that an increase of particle energy diffusion rate in the wave field leading to speeding up of the polarization process is owing not to an increase of field intensity but rather to an increase of radiation hardness.

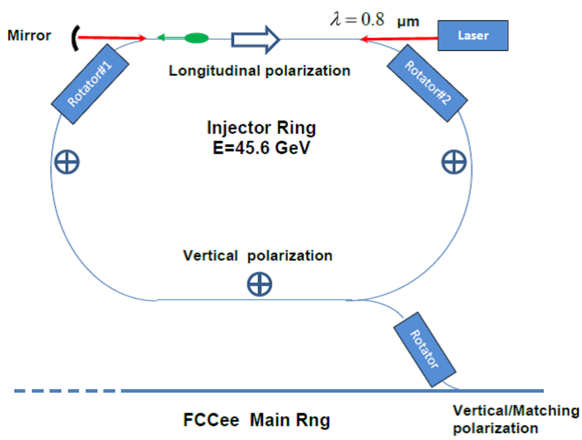


Figure 6: The variant of Hard Photon scheme for FCCee.

Another method, Hard Photons, does not increase a beam energy spread. The possible variant of Hard Photon scheme is presented in Figure 6. In the region of interaction of a cirularly polarized laser beam with electrons the precession axis must lie along the particle velocity. It should be organized in the scheme with localization of longitudinal polarization using the spin rotators. The polarization anywhere outside IR remains vertical. It allows to minimize depolarization effects due to SR in the bending magnets.

Time to reach an extent of beam polarization $\eta$ is given by an equation [4, 5]

$$\tau_w = |\dot{N}_w \zeta (\sigma_\uparrow - \sigma_\downarrow)|^{-1} \ln \frac{1+\eta}{1-\eta}, \quad (19)$$

with $\dot{N}_w$ , an average photon fluence density (cm$^{-2}$·s$^{-1}$);

$$|\sigma_\uparrow - \sigma_\downarrow| = 4\pi r_e^2 \left[ \frac{1+\chi}{2\chi^2} \ln(1+2\chi) - \frac{1+4\chi+5\chi^2}{\chi(1+2\chi)} \right], \quad (20)$$

a difference of the cross sections for electrons with opposite signs of helicity; $\zeta$, a circular polarization extent of photons. The quantity $|\sigma_\uparrow - \sigma_\downarrow|$ characterizes a dependence of the method efficiency in regard to polarization rate on the laser wavelength chosen. In the limit of large photon energies ($\chi \to \infty$) one can obtain a full polarization ($\eta \to 1$) at the cost of losing half of the particles : $N/N_0 \to 1/2$. At that the time of polarization in the wave grows as $\tau_w \propto \chi \ln \chi$ [4, 5]. Thereby, a wish to obtain the polarization close to unity and to keep more of the beam population contradicts a wish to make the polarization process shorter in time.

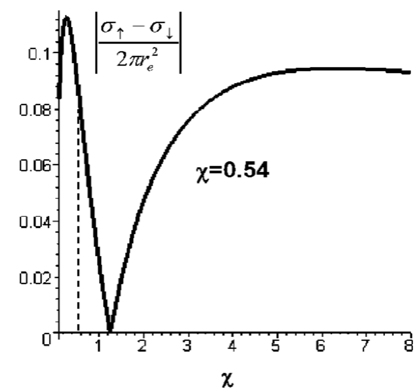


Figure 7: Hard Photon efficiency vs the interaction parameter. The specified value of this parameter is given for $\lambda = 0.8$ $\mu$m at $E = 45.6$ GeV.

Practically, the extent of polarization $\eta \approx 10\%$ is still enough for the precise beam energy calibration by the resonant depolarization technique because of a high efficiency of the laser polarimeter in the FCCee energy range [9]. By this reason one would choose the working wavelength corresponding to not very high values of the $\chi$ parameter. For instance, the wavelength $\lambda = 0.8$ $\mu$m, typical for the Ti:Al203 lasers, corresponds to $\chi = 0.54$ at $E = 45.6$ GeV. Thus the Hard Photon efficiency is close to an optimal one (see Figure7).

An optimal focusing of the laser beams with the help of mirrors and a proper choice of the laser pulse duration in both methods imply that the laser and electron beams are similar in sizes. Examples of the required power and timing performances of the free electron lasers are given in the original papers [4, 5] as applied to the LEP project. The FCCee project is different in regard to its size and the number of bunches. To be competitive the methods basing on the beam-wave interactions should provide the polarization time of about ten minutes or less.

## SUMMARY

- Possibility to apply the Compton scattering of a waveguide wave to measure a beam energy in the FCCee has been considered for the first time. The two wave concept of the Waveguide Compton beam energy monitor has been proposed allowing to diminish uncertainties related to variation of the waveguide transverse sizes. Preliminarily, the method looks promising because provides a reasonable accuracy with high registration efficiency at low wave power.
- One needs to search and consider the competitive schemes to realize the known ideas on application of

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the incident circularly polarized waves for obtaining beam polarization at FCCee.

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## REFERENCES

[1] I. Koop, Talk at this ICFA Workshop.

[2] V.E. Blinov et al., NIM(A) 598 (2009) 23.

[3] N. Muchnoi, private communication.

[4] Ya.S. Derbenev, A.M. Kondratenko, E.L. Saldin, NIM(A) 165 (1979) 15.

[5] Ya.S. Derbenev, A.M. Kondratenko, E.L. Saldin, NIM(A) 165 (1979) 201.

[6] I.F. Ginzburg et al., NIM 205 (1983) 47, 219 (1984) 5.

[7] N. Vinokurov. private communication.

[8] V.I. Telnov, NIM(A) 260 (1987) 304.

[9] A.Blondel, Presentation at TLEP-6 Polarization 2013-10-17.



ISBN 978-3-95450-172-4