ILC undulator based positron source, tests and simulations

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ILC UNDULATOR BASED POSITRON SOURCE, TESTS AND SIMULATIONS*

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Abstract:

An undulator based positron source allows generation of polarized positrons in quantities required by ILC. Here we describe the results of modeling and testing of elements for such a system.

INTRODUCTION

The scheme for polarized positron production was proposed a long time ago in a framework of VLEPP project [1]. The basis of the method is a two stage process, where at first stage the circularly polarized photons generated in helical electromagnetic field and then, at second stage, these photons converted into positrons and/or electrons in a thin (~half radiation length) target. Secondary particles carry longitudinal polarization transferred from the primary photon beam in accordance with theirs energy. In this first publication [1] the gammas considered to be generated by energetic particle in the following substances: in a field of electromagnetic wave, in static magnetic helical field of undulator and in crystals with helical dislocations (helical crystals). In [2] the laser radiation was considered as a specific example of an electromagnetic wave. With application of selection of energetic positrons only, the final polarization increased and defined by the length of undulator (as one needs to compensate partial collection of secondary positrons). For typical length of undulator~175 m, the degree of polarization reaches ~60% and it could reach ~80% with 300 m long undulator. One peculiarity associated with helical undulator scheme is that this system is able to generate *polarized* positrons with degree of polarization ~30% if no energy selection mechanism applied to the positrons at all.

The undulator scheme of positron production has been chosen as a baseline for ILC [3] accommodated from TESLA design [4]. One peculiarity here is that the beam, like in original VLEPP scheme is going through the undulator on its way to IP. One positive moment of this is that the beam can be made having small transverse dimensions as the emittance is small. This allows small aperture in undulator and hence makes engineering problem less severe. From the other hand nonlinear field of undulator could disturb this tiny emittance and polarization of this primary beam while it is going to IP. Considerations show that this is not a problem here however as the beam trajectory remains line-type with accuracy ~1/γ so the nonlinearities cancel each other. So the ILC scheme looks as it is represented in Fig.1

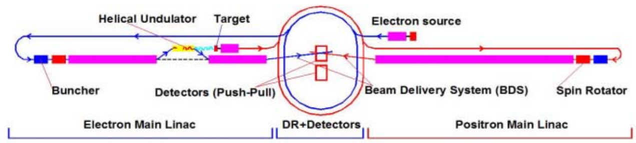

Figure 1: The basic scheme of ILC.

Undulator located at the 150 GeV mark in a chicane, as the energy of quanta radiated on harmonic number n=1 for the undulator with period λ_u comes to ~20 MeV there

$$E_{\gamma n} \cong \frac{n \cdot 2.48\,(\gamma/10^{5})^{2}}{\lambda_u[cm](1+K^{2}+\gamma^{2}\vartheta^{2})}[MeV], \quad (1)$$

where the factor $K = eH\lambda_u/2\pi mc^2 \cong 93.4 \cdot H[T]\cdot\lambda_u[m]$, ϑ stands for the angle in direction to observer. Efficiency of conversion could reach such level, that two initial electrons generate in average three secondary positrons captured (1:1.5 conversion).

Minimal offset in chicane helps in reduction of radiated power (and power density, as the beam size is small) and makes possible emittance perturbation to be smaller also. This chicane could be arranged is the same tunnel without any additional extensions at all, se below.

So one can see that positron source is a complex system which includes a lot of different components and each of these components can be a subject of a separate talk.

GENERATION OF POSITRONS

As the only gamma-quanta can create an electron-positron pair, by all means the positron source must generate the gammas in necessary amounts, able to cover limited acceptance of collection optics. There are few possibilities on how to get gammas, Fig.2.

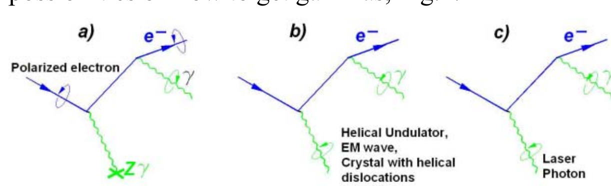

Figure 2: The way to obtain the (polarized) gamma-quanta. a)-the incoming electron is polarized [5], b)-the electron radiates in a helical electromagnetic field of broad nature [1], c)-the laser radiation appointed as a specific example of helical electromagnetic wave [2].

In ordinary conversion system the gammas created as a result of a cascade (shower), developed by the primary non polarized electron (Fig.2, a) with non polarized electron). This is so called generation of gammas by bremstrahlung. Shaking of electron here is going by the field of nuclei. This process is characterized by X_0–radiation length

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$$X_0^{-1} \cong 4r_0^2\alpha\frac{N_0}{A}Z(Z+1)\ln(\frac{183}{Z^{1/3}})[cm^2/gramm], \quad (2)$$

where A –is atomic weight of target substance, $N_0 \cong 6.022\cdot 10^{23}$ is the Avogadro number, Z is the charge of nuclei, factor $Z(Z+1)$ takes into account atom electrons, $\alpha = e^2/\hbar c = 1/137$, r_0 is a classic electron radius.

Despite the thickness of target is significant in this type of conversion, the only outer layers are serving as the source of positrons, which energies in maximum are of the order of the critical, one, ~10MeV. The effective RMS depth l of positron creation is

$$l \cong \langle xx' \rangle / \langle x'^2 \rangle \quad , \qquad (3)$$

where x and x' stand for the transverse coordinate and its derivative, brackets mean average over all phase space. The last expression comes to ~0.8mm for 10-*MeV* positrons. Knowing last number is important for description of target immersed in magnetic field, showing the principal depth, which magnetic field penetration tolerates the process.

In the scheme of positron *production* with gammas obtained by shaking primary electron (or positron) either in a field of static undulator, EM wave or in a laser field, Fig.3 b), c), the gammas represented by a *separate source*. So here the heating the target by primary electron component is absent and all target can be used for positron creation. Thus the target becomes having thickness of the order of latest layer in previous method.

The number of the quants radiated by electron in the presence of the photons (real or virtual from wiggler) can be described in terms of effective length as the following

$$N_\gamma \cong L\sigma_\gamma n_\gamma, \qquad (4)$$

where $\sigma_\gamma \cong r_0^2$, $n_\gamma \cong \frac{H^2\gamma^2}{\hbar\omega}$ is photon density in system of electron, H is magnetic field value, $\omega = 2\pi c/\lambda$ is the frequency of the photon. So the length of interaction goes to $l_\gamma \cong 1/\sigma_\gamma n_\gamma$. For the undulator having the length L

$$N_\gamma \cong Lr_0^2\frac{H^2\gamma^2}{\hbar\omega} \propto 4\pi\alpha\frac{L}{\lambda_u}\frac{K^2}{1+K^2}. \qquad (5)$$

As the length of formation for undulator $\sim\lambda_u$ then this formula reflects the simple fact that the number of radiated photons is equal to the number of radiation lengths, L/λ_u. It is known, that particle radiates α photons on its passage through this distance.

Positron ring can be filled from electron linac also, Fig.3. This magnet system can be made compact; with high-field bending magnets as there are no obstacles from emittance dilution, while the beam irradiates the target.

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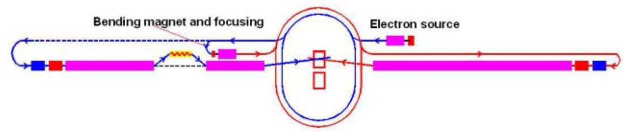

Figure 3: Possible operational scheme for filling positron ring by usage of electron source linac. With stacking and polarized electron source this scheme allows accumulation of polarized positrons.

One additional comment can be made here. In [5] the method for *polarized positron* production was proposed implementing the usage of polarized electrons as a primary source (Fig. 3-a). During bremstrahlung, the longitudinally polarized electron radiates circularly polarized gamma at high edge of spectra. Further on, these polarized gammas become converted into electron-positron pairs in (the same) heavy target, similarly to conversion of undulator gamma-radiation. Polarized electrons obtained from the photocathode, in the same manner, as required for polarized electron source for ILC.

Efficiency of this method could reach ~1.5% [5] i.e. each primary electron generates positron with probability 0.015 with polarization up to ~80% of polarization of primary electron beam (which could be~90%, so coming to ~72% total). So to satisfy the requirements of ILC, the positron beam must be stacked in a damping (cooling) ring. But this is the same yield as for the mechanism for polarized gamma production by usage of Compton back scattering process [6]. By other words the efficiencies of processes shown in Fig.3 a) and c) are the same. For implementation of method [5], one needs to use polarized electron source and insert a target in electron injection line; *no lasers required at all*, as in Fig.3. But still, the method with helical undulator is much more effective way to go. This comment can be considered as a serious argument against the Compton source of positrons for ILC.

Parallel shift in chicane arranged with the help of two bending magnets at each side. Two radially focused quadrupoles at each side accomplish this bend. Total distance occupied by chicane comes to ~350 m minimum; at this distance the RF structures more likely need to be removed. Minimal offset defined by the size of RF modules shadow further on of gamma-ray way as the target located at the distance $\geq$ 180 m from the end of undulator. According to this minimal offset distance might be ~450mm. Bending magnets have active length ~20m each with bending radius ~2km. Calculation of this chicane is rather challenging procedure as the tiny beam emittance makes SR radiation so severe, that without special measures this radiation can damage opposing wall of vacuum chamber [21].

MODELING OF CONVERSION

Diagram on Fig.2 needs to be considered with polarization of secondary positron (electron) as function of its energy E_+ [7], [8]. Main characteristics of Undulator

Radiation (UR) are the energy of quants (1), spectral photon density dN_γ / dE_γ and it polarization as this parameter appears as a factor in final polarization of positron. Expression for spectral density of radiation for undulator having length *L* has a form [18] [14],

$$\frac{dN_\gamma}{dE_\gamma} = \sum_n \frac{dN_{\gamma n}}{dE_\gamma} = \frac{\alpha K^2 L}{\hbar c 2\gamma^2} \sum_{n=1}^{\infty} F_n(K,s), \qquad (6)$$

where $s = E_{\gamma n} / E_{\gamma n \max}$, $E_{\gamma \max}$ defined by (1) for $\vartheta = 0$,

$$F_n(K,s) = J'^2_n(n\kappa) + \frac{1+K^2}{4K^2} \frac{(2s-1)^2}{s(1-s)} J^2_n(n\kappa), \qquad (7)$$

$\kappa = 2K\sqrt{s(1-s)/(1+K^2)}$, J_n stands for the Bessel function of the first kind. Differential cross section referred to the radiation length unit can be represented as the following $d\sigma(E_\gamma, E_+) \cong \sigma_0 dE_+ / dE_\gamma$, where [22]

$$\sigma_0 \cong A/(N_0 X_0) G(E_+, E_\gamma) \qquad (8)$$

stands for total cross-section of photon absorption at the radiation length growing up to 7/9 at high energy,

$$G(x) = x^2 + (1-x)^2 + \frac{2}{3}x(1-x) - x(1-x)/(9\ln(183Z^{-1/3}) \cdot$$

Variation of σ_0 is equivalent of slow variation with energy of the interaction length and requires appropriate correction of target thickness for better efficiency.

The number of positrons generated by a single photon in the target becomes [16]

$$\frac{dN_+}{dE_+ d\tau} \cong 0.4 \frac{\alpha K^2 L}{\gamma^2 \hbar c} \frac{7}{9} (1 - E/E_{\gamma 1})(1 - e^{-7\tau/9}) \quad (9)$$

For E_0=150 *GeV, L*=150 *m*, K^2=0.1, $\tau \cong 0.5$ (rad units)

$$\frac{1}{N_{tot}} \frac{dN_+}{dE_+} \cong 0.2\,[1/MeV] \cdot \qquad (10)$$

More detailed analytical formula for efficiency of conversion per each initial electron taking into account finite length of undulator stands [18]

$$\Delta N_{+1} \cong 2 \cdot 10^{-2} \chi^2 M \delta \frac{K^2}{1+K^2} \frac{z_f}{z_i} (1 - \zeta_{cap}), \qquad (11)$$

where χ is a is a fraction of what is the target radius in respect to the size of the gamma spot at the target distance, $z_{i,f}$ are the coordinates of undulator end and beginning calculated from the target position, ζ_{cap} is efficiency of geometric capture of positrons, $M = L/\lambda_u$ is total amount of undulator periods, δ is thickness of target in radiation length. For

χ = ½ , M=10^4, $\delta = 0.2$, K=1, $\zeta_{cap} = 0.7$, $z_f = M\lambda_u = 2z_i$,

total amount of positrons per electron in undulator comes to $\Delta N_{+1} \cong 3$.

Although analytical calculations found to be accurate, from the very beginning, numerical calculations were thought as a supplemental way to go.

One general question is: how low K-factor could be? One can see from (5) that the number of photons is extremely sensitive to the *K* factor value. From the other hand with increasing the K value the content of higher harmonics also increased. At K≈0.7, the power radiated at the first harmonic comes to 50% of total one. Radiation at harmonics has proportionally higher photon energy, what makes collection of particles more difficult.

To answer these questions few numerical code were used such as KONN [21], CONVER [23], OBRA [26], [27], In particular KONN is start to end computer code realizing Monte-Carlo simulation of radiation in undulator, conversion in target, collection by Li lens and further acceleration.

Argonne Laboratory also began modeling of positron conversion with undulator using EGS4, Geant4 and Fluka [19]. Same type of calculations carried at SLAC [28]

Answer to this question obtained is that K<0.4, λ_u =1cm, L~175 is enough for 1:1.5 conversion in positrons with ~60% polarization. Bigger K~0.9 allows having *L*~30m with polarization ~40%.

TARGET

Power dissipated in a target with traditional method by direct electron/positron conversion becomes so big, that it is not practical for ILC. That is why positron production scheme with undulator was chosen as a baseline for ILC. Even so the target problem remains serious.

The base line for now, is the Titanium rim-target having diameter ~1m spinning at 500 rpm [20]. Thickness of this rim comes to ~1.42cm, close to X_0 /2 for Ti. Such a big thickness introduces additional difficulty for collection optics, which now needs to have the focal depth of the order of the thickness of target.

One possible solution of this could be a *sandwich* type target [21], Fig.8.

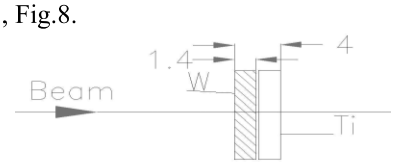

Figure 6: Two-layer target with W as the first one. Dimensions are given in mm

Other possibility is a liquid metal target, Pb/Bi or Hg [24]. In this type of target the metal confined in a profiled duct having Be flange at the exit side of this duct. Some results of this modeling show that temperature rise could be kept at the level of 125°C then the thermal pressure at the first moment comes to ~1*kbar* level. By introduction of focusing and/or some steering of beam in undulator, one can artificially increase the gamma-spot size on the target.

COLLECTION OPTICS

Usage of collection optics has a peculiarity here as the spinning target rim perturbs magnetic field as result of eddy currents in moving metal [25]. So collection optics must be field free in region of target. Description of Li lens and solenoidal lens on can find in [30]

Accelerating structure is important component of positron conversion system. Structure immersed in

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solenoidal field having maximal value up to 40kG, so the room temperature structure with big aperture must be used here. Such structures with appropriate parameters are under development [10], [20]. Structure developed in [20] has one input located close to the target side, indeed the RF power input in [10] made in a symmetric way by usage of two waveguides. What is important here is to locate RF input at the far end of the structure counted from the target.

TEST OF UNDULATORS

Undulators satisfying requirements of positron conversion system very fabricated and tested in Novosibirsk in 1986 as a part of VLEPP program [11]. Pulsed undulator tested had aperture 4mm, period 6mm and could reach K=0.35 with feeding current ~10kA. SC undulator had period 10 mm, aperture ~6mm and could reach K~0.6. Basically these designs served as prototypes for design of undulator for E-166 experiment (see below) and for SC undulators developed at Cornell.

Few undulators were tested at Cornell. Basically they can be grouped in two categories as having 10mm and 12mm periods. Helical iron yoke of appropriate period used in all undulators designs so far. All undulators tested have clear aperture 8mm. Maximum K factor reached for 10mm period undulator is K=0.467 and K=0.83 for 12 mm period. According to our calculation any of these undulators can satisfy 1:1.5 efficiency of conversion. However we considering the reduction of aperture down to 6.25mm which allows having K=0.7 for 10mm period and K=1.2 for 12 mm period. This might be useful for initial period of tuning the ILC. And low K factor helping in obtaining higher degree of polarization could be installed later on by lowering the feeding current.

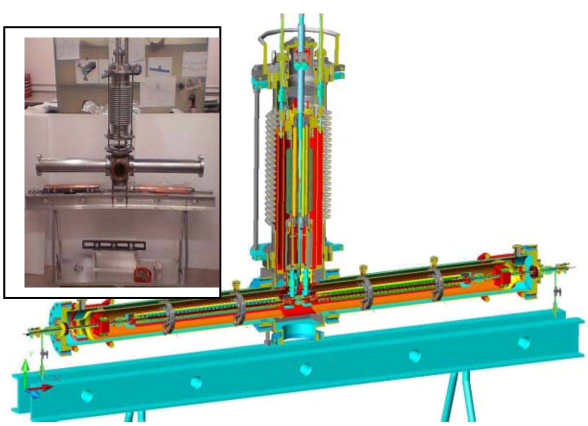

Figure 4: The cross-section of undulator module under assembling in Cornell LEPP. This 1.5 m long prototype model has all elements carried by full 4-m long prototype.

Much attention paid for smooth transition between modules. One can see from Fig.20, that the Copper vacuum chamber in region of cold mass with a help of metal gasket joint to the stainless steel tube covered by thin Copper layer inside. At some distance between LHe cold mass and room temperature flange, there is c thermal contact with 70 ^{o}K Copper shields. Diameters of copper tube in cold mass and the stainless steel transition one are the same so the perturbation due to wake fields is minimal. This transition required only between long segments as for mostly length, the cold mass of one section joint directly to another one with metallic gaskets.

Indeed, in design [9] the transition is rather long and has significant variations in diameter. Mode detailed description about development of undulators in UK on can find in [29].

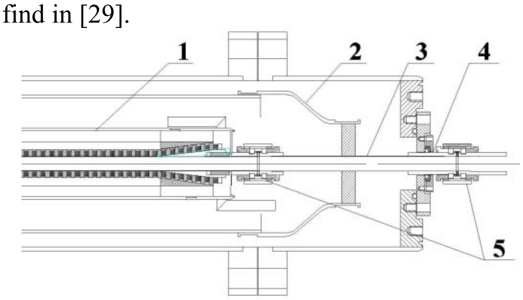

Figure 5: Schematics of transition region between cold mass and the room temperature flange in Cornell undulator. 1—cold mass, 70 ^{o}K shield, 3—StSteel thin wall tube, 4—Wilson type sealant, 5—Conflat® joints.

TEST OF CONVERSION SYSTEM

Recently the test of polarized positron production in experiment E-166 [17] was done successfully. Polarization of positrons ~85% measured in good agreement with calculations. We expect detailed publication soon. Polarization measured by usage of spin dependence in cross section of circularly polarized gammas, propagating in magnetized Iron.

Targets were installed on remotely movable device having few slots for installation of targets of different materials and thickness. It was found, that W target gives~45% higher yield than the Ti target of the same thickness ($0.5X_0$).

CONCLUSIONS

Conversion system using undulator as a source of circularly polarized photons delivers polarized positrons at the exit in the amounts >1.5 per each initial electron/positron at the entrance. This efficiency can be obtained with relatively low K factor <0.4. Main beam of electrons after reaching 150 GeV directed in undulator installed in chicane line with minimal deflection from the linac axis. Aperture of undulator due to small dimensions of the driving (primary) beam could be 6-8mm only. Period of undulator might be 10-12 mm and this well supported by models developed and tested at Cornell and at Daresbury.

Polarization in both beams is extremely powerful tool for High energy physics as it delivers a possibility to prepare more cleanly initial condition and suppress mostly backgrounds. Perturbation of polarization is minimal [12], [13]. We are concluding that *if* Linear Collider will be built in some time at all, it must be able colliding both positrons and electrons polarized. Undulator needs to be made with sections ~4*m* each with total length ~200*m*. Longer undulator-higher polarization can be achieved. With 300 *m*-long undulator polarization can reach 80%. Polarized electrons could be obtained by the same way also.

Experiment E-166, which completed at SLAC, eliminated any doubts about polarized positron production possibilities.

REFERENCES

[1] V.E.Balakin, A.A.Mikhailichenko, "*Conversion System for Obtaining Highly Polarized Positrons and Electrons at High Energy*", Budker INP 79-85, Sept. 13, 1979.

[2] E.G. Bessonov, "*Some Aspects of the Theory and Technology of the Conversion Systems of Linear Colliders*", 15th International Conference on High Energy Accelerators, Hamburg, 1992, p.138.

[3] For ILC Reference Design Report see: http://www.linearcollider.org

[4] TESLA: "*Conceptual Design of a 500 GeV $e^+ e^-$ Linear Collider with Integrated X-ray Laser Facility*", DESY 1997-048, ECFA 1997-182, Vols.1-2, Ed.: R.Brinkmann, G.Materlik, J.Rossbach, A.Wagner, May 1997.

[5] E.A.Bessonov, A.A.Mikhailichenko,"*A Method of Polarized Positron Production*", THP071L, Published in EPAC96, Barcelona, June 9-14, 1996. Proceedings. p.1516, see: http://accelconf.web.cern.ch/AccelConf/e96/ PAPERS/PL/THP071L.PDF.

[6] T.Omori," *ERL based Compton e^+ source for ILC*", ILCWS2007, Proceedings, http://lcws07.desy.de/

[7] H.Olsen, L.Maximon, Phys. Rev., 1959, 114, 887.

[8] V.N.Baier, V.M.Katkov, V.S.Fadin, "*Radiation of relativistic electrons*", Moscow, Atomizdat, 1973.

[9] A. Birch," *ILC Positron Source Helical Undulator Update*", a Talk at ILCWS2007, Hamburg, see ILCWS website- http://lcws07.desy.de/.

[10] L.V. Kravchuk, V.A. Moiseev, A,N. Naboka, V.V.Paramonov, A.K.Skasyrskaya, "*INR Activity in the Accelerating Cavities and Studies*" , a Talk at ILCWS2007, Hamburg, see ILCWS website- http://lcws07.desy.de/.

[11] A. Mikhailichenko, "*Conversion System for Obtaining Polarized Electrons and Positrons at High Energy*", Dissretation, Novosibirsk 1986, Translation in CBN 02/13, Cornell, 2002.

[12] E.A. Perevedentsev, V.I. Ptitsin, Yu.M. Shatunov, "*Spin behavior in Helical Undulator*". Int. J. Mod. Phys. A, Proc. Suppl. 2A (1993) 170-172.

[13] E.A. Kushnirenko, A. A. Likhoded, M.V. Shevlyagin, "*Depolarization Effects for Collisions of Polarized e^+e^- Beams*", IHEP 93-131, SW 9430, Protvino 1993.

[14] A. Mikhailichenko, CBN 02-10, Cornell LEPP,2002.

[15] Yu. Ivanyushenkov, *et.al*, "*Development of Helical SC Undulator for a Polarized Positron Source*", PAC2005, Knoxville, Proceedings, pp.2295-2297.

[16] A. Mikhailichenko, "*Positron Source for ILC. A Perspective*", CBN 06-1, Cornell 2006, http://www.lns.cornell.edu/public/CBN/2006/CBN06-1/CBN06-1.pdf

[17] G. Alexander *et al.,"Undulator-based production of polarized positrons: A Proposal for the 50-GeV beam in the FFTB*", SLAC-TN-04-018, SLAC-PROPOSAL-E-166, Jun 2003. 67pp.

[18] E.A.Bessonov, A.A.Mikhailichenko, "*Some Aspects of Undulator Radiation Forming for Conversion System of the Llinear Collider*", Budker INP-1992-43, Jun 1992. 26pp; see http://ccdb4fs.kek.jp/cgi-bin/img_index?9302032

[19] W. Liu,; W.Gai, " *The Undulator Based ILC Positron Source: Production and Capturing Simulation Study – Update*", [ILC-NOTE-2007-009] http://ilcdoc.linearcollider.org/record/6947

[20] V.Bharadvaj, "*May 2007 ILC Positron Source Update*", a Talk at ILCWS2007, Hamburg, see ILCWS website- http://lcws07.desy.de/.

[21] A. Mikhailichenko, "*The status of positron conversion System Development at Cornell*", ILCWS2007, Proceedings, http://lcws07.desy.de/ , CBN 07-6, Cornell LEPP, see: http://www.lns.cornell.edu/public/CBN/2007/CBN07-6/CBN07-6.pdf

[22] W. Heitler. "*The Quantum Theory of Radiation*". Third edition, Oxford, 1954.

[23] A.D.Bukin, "*Choice of optimal Positron Converter for Low Energy Beam*", (in Russian), Preprint INP 90-100,Novcsibirsk, 1990.

[24] A.Mikhailichenko," *Liquid Metal Target for ILC*", MOPLS108, Published in EPAC06 Proceedings, Edinburg, June 26-30, 2006.

[25] A.Mikhailichenko*,"Issues for the Rotating Target"*, CBN-07-02, 2007. see: http://www.lns.cornell.edu/public/CBN/2007/CBN07-2/CBN07-2.pdf

[26] A.D.Bukin, A.A.Mikhailichenko, "*Optimized target strategy for polarized electrons and positrons*", BUDKER-INP-1992-76, Oct 1992. 37pp

[27] A. Mikhailichenko, "*Polarized e^+,e^- Production Based on Conversion of Gammas, Obtained from Helical Undulator*", CLNS 01/1758, Cornell University, Ithaca, NY 14850July 11, 2001, a talk at SNOWMASS2001

[28] F.Zhou, Y.Batygin, Y.Nosochkov, J.C.Sheppard, M.D.Woodley,"*Start-to-end Beam Optics Development and Multi-particle Tracking for the ILC Undulator-Based Positron Source*", SLAC-PUB-12239, Jan 2007. http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-12239.pdf

[29] Yu. Ivanyushenkov, *et. al.* "*Development of a Full Scale Superconducting Undulator Module for the ILC Positron Source*", THPMN071, PAC2007.

[30] A.Mikhailichenko, "*Collection Optics for ILC Positron Target*", THPMS012 , PAC2007.

1-4244-0917-9/07/$25.00