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Review Article

A Brief Review of the Gamma Ray Free Electron Laser Undulator Design Parameters for International Linear Collider Operation

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Abstract: In this paper, we make a review of the International Linear Collider design with regard to its positron source. The properties of the intense gamma ray undulator radiation of the dedicated free electron laser is reviewed. We review the discussions about the proposed undulator parameters to obtain an efficient operation of the positron source. The proposals and experimental results about the optimization of the positron beam yield, undulator properties, the injected electron beam energy, polarisation qualities of the produced gamma rays and the positron beam, are discussed. Alternative ideas and suggestions about the use of excess gamma rays in other nuclear energy experiments or the use of positrons in the undulator instead of electrons are also mentioned.

Keywords: *Free electron laser, helical undulator, international linear collider, superconducting undulator*

Uluslararası Doğrusal Çarpıştırıcı Operasyonu için Gamma Işını Serbest Elektron Lazeri Salındırıcı Tasarımının Kısa Bir Gözden Geçirilmesi

Özet: Bu makalede uluslararası doğrusal çarpıştırıcı tasarımının pozitron kaynağına ilişkin bir derleme yaptık. Şiddetli gamma ışını undulatör ışımasına yönelik serbest elektron lazerinin özelliklerini derledik. Pozitron kaynağının etkin çalışması için önerilmiş salındırıcı parametreleri tartışmalarını derledik. Pozitron demeti kazanımı, salındırıcı özellikleri, enjekte edilen elektron demetinin enerjisi, üretilen gamma ışını demetinin ve pozitron demetinin kutuplanma kalitesine ilişkin önerileri ve deneysel sonuçları tartıştık. Aşırı gamma ışınının düğer nükleer enerji deneylerinde kullanılması ile ilgili veya undulatörde elektronlar yerine pozitronların kullanılması ile ilgili alternatif düşünceleri ve önerileri belirttik.

Anahtar Kelimeler: *Helezon undulatör, serbest elektron lazeri, süperiletken undulatör, uluslararası doğrusal çarpıştırıcı.*

1. Introduction

The International Linear Collider Project (ILC) [1] is aimed at high energy collision of high quality lepton beams, mainly electrons and positrons among many other applications like low emittance muon beam collisions for the study of what is known as the Standard Model of particle physics and further other nuclear physics applications. The main idea of such a tool is to produce low emittance polarized positron and electron beams of high quality, both spin polarized in the forward direction is deemed to be necessary for the experimental investigations [2, 3]. Omori et.al. [4] proposed an electron beam of energy 1.28 GeV to be shone on by a circularly polarized laser light of wavelength $\lambda = 532nm$ at an opposing grazing incidence angle. This scheme produces circularly polarized gamma ray photons by Compton back scattering mechanism. Cardman reports obtaining circularly polarized bremstrahlung radiation obtained from circularly polarized electrons which then produces circularly polarized positrons in the same material made up of heavy nuclei by pair production [5]. What seems to dominate as the most appropriate proposal appears to be that of using an undulator

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[6] to generate a circularly polarized free electron laser gamma ray beam to hit a resilient material target and hence generate polarized positrons at an unprecedented rate and quality [7,8].

In this study we make an overview of the ongoing discussions to elucidate the theory and the developing technology. The discussion is an ongoing one being supported by simulations and experimental demonstrations of techniques to be used as of today.

2. Undulator Structure for a Gamma Ray Laser

The basic principles of free electron lasers (FELs) were initially suggested by J.M.J. Madey as early as 1970`s. [9]. Its first operation was as an oscillator and used to amplify the radiation output from a CO_2 Laser [10]. However, it was soon recognized that the system is widely scalable and the wavelength could be tuned by adjusting the physical parameters. The laser operation could be pushed into higher frequencies where the only limitation seemed to be the current day technology. Starting with FEL's operating at Infrared wavelengths, whose operation is ubiquitous these days [11-12], the FEL theory [13-14] and the FEL technology have finally reached the Vacuum Ultraviolet and Soft X-Ray Region of the spectrum in terms of operation [15].

FEL is not a conventional method of radiation generation like that of standardized atomic and molecular lasers. Therefore, one needs to keep working on improving the main qualities of FEL light. In the sections to follow we discuss how a gamma ray free electron laser (GRAYSER) can have the main four properties of a laser. These properties are directionality, monochromaticity, coherence and high power [16]. How and why this particular source is preferred as the main driver of a positron light source will also be discussed shortly

2. Elliptical B-Field Undulator Structures

A planar undulator is formed of a series of bar magnets arranged in such a way so as to create an oscillating magnetic field on the transverse direction to a certain z −axis as shown in Figure 1. This permanent magnet structure to form a sinusoidal transverse magnetic field structure is referred to as the Halbach configuration. The transverse magnetic field formed inside the undulator in Figure 1 are oscillating in the vertical y −direction in a sinusoidal manner. If a charged particle beam is incident along the z −axis it will make a slalom motion in the $x-z$ plane as it moves along the z −direction.

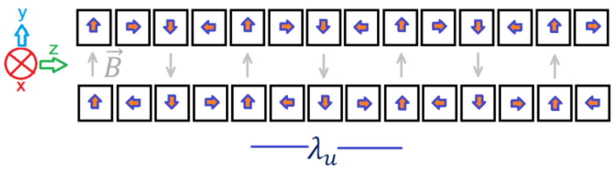

Figure 1. Ideal planar undulator in the Halbach configuration.

In Figure 1, arrows on the bar magnets show the direction of the magnetic fields of the individual bar magnets and arrows in between the arrays show the transverse $\vec{B}$ −field directions on the z −axis. The $\vec{B}$ −field along the axis is expressed as a sinusoidal transverse magnetic field of the form [17]

$$\vec{B} = \hat{y} B_{y_{max}} \sin\left(\frac{2\pi}{\lambda_u} z\right) \quad (1)$$

where $B_{y_{max}}$ is the peak transverse on axis field and where λ_u stands for the undulator period. This $\vec{B}$ −field leads to a transverse oscillation of the e^- trajectories along the x −direction as the electrons are moving along the z −direction for this particular configuration.

It is only an extension of the same idea at this stage to add another oscillating magnetic field structure about the z −direction based on the same principle but this time along the x −direction as well, in which case we have a magnetic field oscillating along the x −direction just as well as along the y −direction. We refer to this magnetic field structure made up of arrays of permanent magnets as an Elliptical $\vec{B}$ −field structure and the general formula is given as

$$\vec{B} = \hat{x} B_{x_{max}} \sin\left(\frac{2\pi}{\lambda_u} z\right) + \hat{y} B_{y_{max}} \sin\left(\frac{2\pi}{\lambda_u} z - \alpha\right) \quad (2)$$

where $B_{x_{max}}$ and $B_{y_{max}}$ refer to the transverse magnetic field maxima along the x and y directions which are not necessarily the same. The propagation axis of the electron beam is along the z −direction. In Equation (2), λ_u stands for the wavelength of the periodic magnetic field along the z −axis, and α stands for the relative phase difference between the permanent magnet structures. The first pair of undulator sequences form a transverse periodical field along the x −direction and the other array form a periodic magnetic field along the y −direction and both having the exact same periodicity λ_u along the z −direction. The relative phase α can be adjusted by shifting the relative positions of the magnets along the z −axis. For the special case of $B_{x_{max}} = B_{y_{max}} = B_o$ and either $\alpha = \frac{\pi}{2}$ or $\alpha = \frac{3\pi}{2}$ are satisfied, the elliptical magnetic field expression reduces to a helical magnetic field of the form [18]:

$$B_x = B_o \sin\left(\frac{2\pi}{\lambda_u} z\right) \quad (3)$$

$$B_y = B_o \cos\left(\frac{2\pi}{\lambda_u} z\right) \quad (4)$$

An alternative set up to obtain an undulating magnetic field consists of two helical windings about the same axis with the same helicity as shown in Figure 2 called the double helix undulator structure. This configuration may also produce an elliptical magnetic field about the axis provided that the currents flow in the opposite direction so as to cancel out the magnetic fields in the axial direction. The relative phase is controlled by the relative shift d and the periodicity of the helices are that of the undulator period. When these wires are superconductors, they can bear very high electric currents on the order of kA resulting in an extremely large periodical magnetic field vector along the transverse direction to the z −axis given by Equation 2. Under careful adjustment to magnetic fields of the form of Equation pair 3 and 4 i.e., helical magnetic fields can be realized[19].

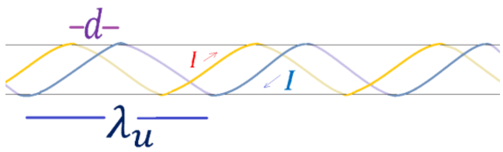

Figure 2. The Double Helix Undulator.

The design options for a Helical Undulator structure had been discussed extensively whether it should be a Halbach configuration fixed magnet structure or a superconducting helical structure and some preliminary tests have been performed. Some experiments and demonstrations have been carried out in favor of the latter [20-23].

4. Directionality

If an electron beam with a relativistic velocity is injected along the axial direction within vacuum, its trajectory will be bent and it will follow an elliptical helical path itself along the axis. A charged particle at relativistic velocity whose trajectory is bent by a magnetic field emits what is known as Synchrotron Radiation of broad spectrum into a cone of opening angle $1/\gamma$ where γ stands for the relativistic energy parameter of the moving electron beam. The total energy of the electron is

$$E = \gamma m_e c^2 \tag{5}$$

where m_e is the electron mass and c denotes the speed of light. Since in principle the electron can be accelerated to a velocity arbitrarily close to c the speed of light, the relativistic energy factor γ may be assumed to have quite large values as well, which in turn means that the corresponding Synchrotron radiation is emitted into an even sharper cone as the electron energy reaches higher values. For the case of ILC (International Linear Accelerator) project, the total energy is set as $E = 150\ GeV$ leading to $\gamma \sim 293542.67949$, hence we can say that the opening angle is $\frac{1}{\gamma} \sim 3.40666 * 10^{-6}$ radians which in fact is extremely directional.

5. Emitted Wavelength

In general the equation for the emitted wavelength of an Elliptical Undulator radiation is given as

$$\lambda_i = \frac{\lambda_u}{2i\gamma^2}\left\{1 + \frac{K_x^2}{2} + \frac{K_y^2}{2}\right\} \tag{6}$$

where

$$K_x = \frac{e\lambda_u B_{x_{max}}}{2\pi m_e c} \tag{7}$$

and

$$K_y = \frac{e\lambda_u B_{y_{max}}}{2\pi m_e c} \tag{8}$$

which are referred to as the $x-$ and $y-$deflection parameters respectively. K_x and K_y are defined based on the electron charge e, the electron mass m_e and the speed of light c in vacuum. For a general wiggler equation i denotes the harmonic integer harmonic number, but for a helical undulator the only existent mode is the fundamental harmonic $i = 1$. In SI units these equations can be quantified as

$$K_x = 93.3728962005\lambda_u[metre]B_{x_{max}}[Tesla] \tag{9}$$

$$K_y = 93.3728962005\lambda_u[metre]B_{y_{max}}[Tesla] \tag{10}$$

The ratio of the maximum deflection angle of the electron trajectory to the opening angle of the synchrotron radiation is the physical definition of the deflection parameter. For a helical undulator, $K = K_x = K_y$ and only the fundamental mode with $i = 1$ is supported.

The ILC Undulator parameters are $B_o = 0.88\,T$ and $\lambda_u = 0.0115$ m, hence the deflection parameter yields $K = 0.94493370954906$, and since $K < 1$ we refer to the magnetic field structure term wise as an undulator unlike the case of $K > 1$ where we would refer to is as a wiggler. For an undulator, the emitted synchrotron radiation cone will cover the trajectory of the electrons ahead leading to stimulated emission with a mechanism known as Self Amplified Spontaneous Emission (SASE). The central wavelength of the emitted radiation is $\lambda = 126.314423$ fm, yielding a single photon energy of

$$E_\gamma = \frac{hc}{\lambda e} = 9.81552182337 \text{ MeV} \tag{11}$$

This gamma ray photon has an energy which is way larger than the threshold necessary to cause an e^-e^+ pair production by a gamma ray photon in the vicinity of a heavy mass, which is 1.22 MeV, merely twice the rest mass energy of an electron-positron pair. What is even more important is that the radiation produced by a helical undulator will provide a circularly polarized radiation in which case positron beam produced will have their spin dictated to be in the forward direction, which is an important parameter for nuclear physics experiments. Another important parameter is the beam brightness, just as well as the directionality of the beam, we need more photons to hit the target and hence to cause a larger number of pairs to be produced. The undulator parameters are tabulated in Table 1.

The number of positrons produced for every photon passing per second is referred to as the positron yield and it is a function of undulator parameters and the injected electron beam energy. Higher energy of the incoming e- beam leads to a higher positron yield however the polarization is compromised which is even more important so one does not prefer very high electron beam energies at the TeV range [24].

Table 1 Parameters of the FEL Operation [18,27,28]

e^- beam energy [GeV]	150
Relativistic Energy Factor	293542.67949
Undulator Period [m]	0.0115
Peak Magnetic Field [T]	0.88
Deflection Parameter	0.94493370954906
Ray wavelength [m]	$126.31442 * 10^{-15}$
Single Photon Energy [MeV]	9.81552182337
Ray opening angle [rad]	$3.40666 * 10^{-6}$
Positron yield per photon	1.5

6. Power, Bandwidth, Coherence, Monochromaticity

Noting that the number of undulator periods N contributes to increasing the total emitted intensity of the radiation as [25]

$$I = I_o N^2 \tag{12}$$

where I_o denotes the intensity of radiation emitted from a single period of the undulator. A larger number of undulator periods N also contributes to narrowing down the emitted radiation bandwidth $\Delta\nu$ of the gamma rays of frequency ν as

$$\frac{\Delta\nu}{\nu} = \frac{1}{N} \tag{13}$$

By using the fundamental definition of the speed of light, frequency and the emitted wavelength $c = \nu\lambda$ one can easily derive the wavelength bandwidth $\Delta\lambda$ and the frequency bandwidth $\Delta\nu$ relation as

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\nu}{\nu} \quad (14)$$

The proposed number of periods for the undulator is $N = 155$, hence we can see an improvement in the intensity of the emitted radiation from a single undulator section with an order of four (namely $> 10^4$) and also a narrowing down of the bandwidth by a factor of N for an ideal undulator. The simulations HUSR/GSR software packages indicate a peak about 10 MeV for emitted photons and a bandwidth of about 5% for the main spectral lobe [26]. The projected positron production rate is estimated to be about 10^{14} e^+ per second, the best possible polarized positron source proposed so far [24]. We can take a moment to appreciate the coherence degree of this radiation source considering that its wavelength is merely 126 fm, pretty much comparable to the size of larger nuclei. The length of one period of the undulator being $\lambda_u =$ 1.15 cm, with the number of periods N=155 leads to a length of 178.25 cm and with a period of N=88 it leads to an undulator length of 101.2 cm. The proposal is to use 84 identical sequential modules of undulators to increase the intensity even further. The e^- beam goes through an undulator module to produce gamma rays, and then the electron beam goes through operations through magnetic dipoles for correction back to the axis and used again and again in consecutive modules to increase the intensity of the final radiation. The total length of the undulator modules section reaches 147 m [19]. The radius of the helix is projected as 4.5 mm. From the vacuum technology perspective, it is preferable to have a smaller tube to keep in ultrahigh vacuum, hence a smaller radius just as well as a shorter undulator period is admissible. Unfortunately, the superconducting materials are becoming brittle under about a period of 1cm limiting the lower limit for the length of the undulator section. The main limiting factor on the fabrication of the superconducting helical undulators is that current methods become more laborious and tedious for shorter undulator periods.

7. Conclusion

We have discussed the development of ideas and design principles for the ILC positron source gamma ray FEL. The injected e^- beam into the helical undulator has an energy of 150 GeV and, after it is utilized, 147 GeV output e^- beam is intended to be gained back with a diverter structure in the original 2008 design [27]. The produced highly directional gamma ray photons are meant to hit a highly resilient and durable material target made of an Titanium alloy (Ti_6Al_4V), which nevertheless is made to spin to avoid material damage under intense gamma ray laser exposure [28].

The design proposals have considered that the excess photons would be dumped, but taking into account that only 7% of the produced gamma rays can used for pair production in the best case scenario, and 93% goes to dump unless it is utilized by other means [26]. It was suggested to use the excess gamma ray photons for nuclear physics experiments at another station.

We reckon that the design principles of ILC FEL Polarized Gamma Ray Laser Source may be useful also for an optimization for a Vacuum Ultraviolet or a Soft X-ray FEL for the study of materials science. Such XFEL projects are currently underway both at the UK and at Turkey. A study for the details of the build-up of a helical undulator for an XFEL operation is underway in further detail.

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References

[1] Philip B. , (2019), International Linear Collider A Global Project, arXiv: 1903.01629.

[2] Omori T., (1999). A polarized positron beam for linear colliders, KEK-Preprint-98-237.

[3] Potylitsyn A.P., (2002), Laser Polarization of Positron Beam, arXiv:physics/0203059

[4] Omori T., Fukuda M., Hirose T., Kurihara Y, Kuroda R., Nomura M., Ohashi A., Okugi T., Sakaue K., Saito T, Urakawa J., Washio M., and Yamazaki I., (2006). Efficient Propagation of Polarization from Laser Photons to Positrons through Compton Scattering and Electron-Positron Pair Creation, *Phys. Rev. Lett*. 96, 114801.

[5] Cardman, L.S., (2018). The PEPPo method for polarized positrons and PEPPo II, *AIP Conference Proceedings 197*0, 050001, AIP Publishing.

[6] Furletova Y. and Mantry S., (2018). Using polarized positrons to probe physics beyond the standard model. *AIP Conference Proceedings 1970*, 030005, AIP Publishing.

[7] Moortgat-Pick G.et.al, (2008). Challenge of Polarized beams ant Future Colliders, Journal of Physics: Conference Series 110, 112004, IOP Publishing.

[8] Alexander G. et al., (2008). Observation of Polarized Positrons from an Undulator-Based Source *Phys. Rev. Lett.* 100, 210801, APS Publishing.

[9] Madey J.M.J. (1971). Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field *J. Appl. Phys.* 42,1906-1913, AIP Publishing.

[10] Deacon D.A.G., Elias L.R., Madey J.M.J., Ramian G.J., Schwettman H.A. and Smith T.I., (1977). First Operation of a Free-Electron Laser *Phys. Rev. Lett.* 38, 892-894, APS Publishing.

[11] Schöllkopf W., Gewinner S., Erlebach W., Heyne G., Junkes H., Liedke A., Platschkowski V., von Helden G. , Zhang W., Meijer G.., Bluem H., Davidsaver M., Dowell D., Jordan K., Lange R., Loos H., Park J., Rathke J., Todd A.M.M., Young L.M., Lehnert U., Michel P., Seidel W., Wünsch R. and Gottschalk S.C., (2012). First Lasing of the IR FEL at the Fritz-Haber-Institut Berlin, In *Proceedings of FEL 2012 MOOB01, Nara, Japan*, (pp. 1-4).

[12] Benson S., Beard K., Biallas G., Boyce J., Bullard D., Coleman J., Douglas D., Dylla F., Evans R.,Evtushenko P., C. Hernandez-Garcia C., Grippo A., Gould C., Gubeli J., Hardy D., Hovater C.,Jordan K., Klopf M., Li R., Moore W., Neil G., Poelker M., Powers T., Preble J., Rimmer R.,Sexton D., Shinn M., Tennant C., Walker R., Williams G., and Zhang S. (2007). High Power Operation of the JLAB IR FEL driver accelerator, In *Proceedings of PAC07, Albuquerque, New Mexico, USA*, (pp 79-81).

[13] Rossbach J, Dohlus M. and Schmüser P.,(2008). *Ultraviolet and Soft X-Ray Free Electron Lasers, Introduction*

to Physical Principles, Experimental Results, Technological Challenges, Springer Verlag.

[14] Atwood D., (1999). *Soft X-Rays and Extreme Ultaviolet Radiation Principles and Applications*, Cambridge University Press, New York.

[15] Brinkmann R., Schneidmiller E.A. and Yurkov M.V., (2010). Possible operation of the European XFEL with ultra-low emittance beams, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, V616(1), (pp 81-87).

[16] Wilson J. and Hawkes J., (1998). *Optoelectronics: An Introduction*, Prentice Hall.

[17] Smolyanov N., Motion of electrons in planar idela undulator, In: Accelerator Physics Radiation Safety and Applications, Ishaq Ahmad and Malek Maaza (eds), Intechopen, 2008.

[18] A. Alrashdi., Bailey I. and Newton D., (2015), Realistic Undulators for intense Gamma Ray Beams at Future Colliders, *6th International Particle Accelerator Conference, IPAC 201 TUPJE0557*, (pp.1756-1758), JacoW Publishing.

[19] Onuki H., Polarizing Undulators and Wigglers, Wigglers, Undulators and their Applications, In: Onuki H. and Elleaume, R. (eds), Taylor & Francis, New York, pp.214-236, 2003.

[20] Scott D.J, Appleton S., Clarke J.A., Malyshev O.B., Shepherd B.J.A., Todd B., Baynham D.E., Bradshaw T., Brummitt A., Carr S., Ivanyushenkov Y., Rochford J., I. Bailey I.R., Cooke P., Dainton J.B., Malysheva L.I., Barber D.P., and Moortgat-Pick G.A., (2007) Selection of the optimum magnet design for the international linear collider positron source helical undulator, *Physical Review Special Topics, Accelerators and Beams*, 10, 032401, 1-11.

[21] Clarke J.A., Bailey I.R., Baynham E., Bradshaw T.W., Brummitt A., Bungau A., Carr F.S., N.A. Collomb N.A., J. Dainton J., Hartin A.F., S. Hesselbach S., K.M. Hock K.M., Ivanyushenkov Y., Jenner L.J., Lintern A., O.B. Malyshev O.B., L.I. Malysheva L.I., Moortgat-Pick G.A., Rochford J., Ryder N.C., D.J. Scott D.J., B.J.A. Shepherd B.J.A. and L Zang L. (2008), Construction of a full scale superconducting undulator module for the international linear collider positron source, *Proceedings of 11th European Conference EPAC 2008,* Genoa, Italy, pp.709-711.

[22] Kim S.H. and Doose C.L., (2007), Development of a model superconducting helical undulator for the ILC Positron Source, *Proceedings of IEEE Particle Accelerator Confeerence PAC07, Albuquerque, New Mexico, USA*, pp 1136-1138, IEEE.

[23] Ivanyuchenkov Y., Baynham E., Bradshaw T., Brummitt A., Carr S., Lintern A., Rochford J., Clarke J.A., Malyshev O.B., Scott D.J., Shepherd B.J.A., BaileyI.R., Cooke P., Dainton J.B., Malysheva L., Barber D.P. and Moortgat-Pick G.A. (2007), Development of full scale superconducting undulator module for the ILC positron source, *Proceedings IEEE Particle Accelerator* Conference *PAC07, Albequerque, New Mexico, USA,* pp 2862-2864, IEEE.

[24] Zhang L., Wolski A., Korostelev M. and Bailey I. (2010), Undulator Based Positron source optimization for CLIC, *Proceedings of IPAC`10, Kyoto, Japan*, pp.4128-4130, IEEE.

[25] Dattoli G., Renieri A. and Torre A., (1993) Lectures on the Free Electron Laser Theory and Related Topics, World Scientific Publishing Company, Singapore.

[26] Alrashdi A., Bailey I. and Newton D., (2014). Possible uses of gamma rays at future intense positron sources, *5th International Particle accelerator conference, IPAC2014,* Dresden, Germany, (pp.586-588) JACoW Publishing.

[27] Clarke J.A., Bailey I.R., Baynham E., Bharadwaj V., Bradshaw T.W., Brummitt A., Bungau A., Carr F.S., NCollomb N.A., Dainton J., Dollan R., Gai W., J. Gronberg J., Hartin A.F., Hesselbach S., Hock K.M., Ivanyushenkov Y., Jenner L.J., Laihem K., Lintern A., Liu W., Lohse T., Malyshev O.B., Malysheva L.I., Mikhailichenko A.A., Moortgat-Pick G.A., Piggott W.T., Riemann S., Rochford J., Ryder N.C., Schaelicke A., Scott D.J., Sheppard J.C., Ushakov A. and L. Zang L., (2008). The design of the positron source for the international linear collider, *Session on Linear colliders, Lepton accelerators and new acceleration techniques*, *Proceedings of EPAC08,* Genoa, Italy, (pp.1915-1917).

[28] Jenkins M. and Bailey I.R., (2012). Novel Designs for Undulator Based Positron Sources, *Proceedings of IPAC2012,* New Orleans, Louisiana, USA, (pp.1485-1487).