**EUROTEV-Report-2005-015-1**

# Preparing the Decision: Conventional versus Undulator based Positron Source

Klaus Floettmann

DESY

August 2005

*No apologies in our joint quest for scientific truth.* J. Sheppard

## Compton Sources

Compton backscattering sources utilize backscattered laser light for the production of polarized positrons. Different schemes have been proposed, all requiring complex electron beam manipulations and high power lasers. The feasibility of this kind of source is not demonstrated up a point comparable to undulator based or conventional sources. None of the proposed schemes is a viable option for ILC at this point.

The advantage of Compton based sources as compared to undulator based sources is that they can be operated independently of the main linac. The impact of the linked operation of an undulator based source on the overall machine performance is still under discussion, but recent results [1] show that it has been overemphasized in previous publications [2]. The complexity of Compton based concepts and the high requirement on systems (high brightness electron beams, very fast kickers, lasers, alignment of multiple laser-electron interaction points), often beyond what is currently available, will have a strong impact on the availability of this kind of source. It is unlikely that the overall availability of a Compton based source can compete with an undulator based source even though a stand alone operation of a Compton based source is possible. Thus not only the viability of a Compton based source needs to be demonstrated but also the improved availability.

The generation of radiation in a helical undulator can be described by Compton scattering of circularly polarized, monoenergetic virtual photons off the electron beam traveling through the undulator. The radiation characteristics of a weak ($K \ll 1$) helical undulator corresponds to the radiation obtained by scattering laser light off an electron beam in all aspects as spectral and angular distribution, polarization and correlation between energy, emission angle and polarization. In case of a stronger undulator ($K \approx 1$) higher harmonics appear in the radiation spectrum corresponding to non-linear Compton scattering. In simulations positron polarization levels up to 90% can be realized irrespective of the strength of the undulator [3]. Practical polarization levels are limited to ~ 60%. To reach higher polarization levels requires scraping off a large fraction of the positron beam and is ineffective. This argument holds for undulator based sources for which the production of a large amount of positrons is relatively easy, but even more for Compton based sources where this is much more difficult.

## Conventional vs undulator based source

### Conventional source

The conventional positron source proposed in [4] assumes a primary electron beam energy of 6.2 GeV and the nominal ILC beam current and bunch structure for the positron beam generation. At the optimized target thickness (4.5 $X_0$, Tungsten) about 13 positrons per incoming electron leave the target. In order to design the source with a 50% safety margin 1.5 positrons per electron, matched to the transverse and longitudinal acceptance of the damping ring, have to be transported up to the damping ring, which means that 11.5% of the positrons at the target have to be captured in the section following the target.

It is assumed, that the target (in the case of a single target design) rotates with a velocity of 360 m/s at its periphery (target diameter 2 m, 3400 RPM) [5] so that the heat load induced mechanical stress is reduced. Still a minimum rms spot size of 2.0 mm of the electron beam impinging on the target has to be guarantied in order to get the mechanical stress in the target under control.

A further increase of the positron production would require an increase of the primary beam energy or current and a corresponding increase of the rotational velocity of the target or of the spot size on the target. Since the rotational speed seems to be at its limit (otherwise it would be possible to increase it right away, reduce the spot size and hence improve the capture efficiency), an increase of the spot size seems to be necessary, which unfortunately leads to a reduction of the capture efficiency. Without going into details it can be concluded, that the production for this source scales less than linear with the primary beam power. A significant increase of the positron production is not possible due to technical limitations in the target design (mechanical stress, rot. velocity). Hence it is mandatory to achieve a capture efficiency of 11.5% in the positron capture section which requires a certain acceptance of the damping ring.

## Undulator based source

Key features of an undulator based positron source are a smaller positron beam divergence resulting in a higher capture efficiency and a large safety margin concerning mechanical stress in the target. For the present design an rms photon beam spot size of 0.7 mm and a velocity of 50m/s at the periphery of the target (target diameter 0.8 m, 1200 RPM) are assumed [6, 7]. From the point of view of mechanical stress in the target a significant increase of the photon beam power is acceptable. Obviously this requires a longer undulator and results in a larger energy loss of the primary electron beam, it allows however to design the positron source for a smaller damping ring acceptance. The layout of the positron source can hence be based on an overall cost and performance optimization.

## Yield calculations

For the yield calculations presented below a somewhat simplified and idealized capture optics has been assumed. As a result of these simplifications (e.g. ideal fields, no miss alignments) all results might be considered as being too optimistic. On the other hand some optimizations in the set up might still be conceivable and need a further detailed investigation. For example the option to decelerate the positrons in order to improve the bunching has not been investigated here. However, improvements and deteriorations act on both sources in a very similar way. The results obtained here present therefore a valid comparison of both types of positron source.

The field distribution of the focusing solenoid assumes an ideal field starting with a 6 T peak field at the exit of the target which is adiabatically tapered down to an end field of 0.5 T. The taper parameter is at the optimal value, i.e. 30 $m^{-1}$ for the undulator based source and 60 $m^{-1}$ for the conventional source. Further downstream the solenoid field stays constant without interruptions. Shortly before the end point of the calculation the

field ends with a smooth edge field, so that the yield estimation is done outside of the solenoid field. Accelerating cavities are located inside the solenoid, starting 20 cm downstream of the target in all cases. Field profiles and maximum gradients are based on the CDS structures as developed in the framework of the TESLA TDR [7 - 9]. The transverse RF fields are assumed to scale linearly with the radius. Nonlinearities which occur close to the cavity iris are ignored. The radius of the cavity irises is 23 mm and the average positron energy at the end of the section is ~120 MeV.
Since the subject of this section is the capture efficiency as function of the damping ring acceptance, undulator parameters are not discussed. Details of the photon spectrum have only small impact on the capture efficiency and can hence be ignored at this point. For the undulator based source an undulator spectrum with an energy of the first harmonic of 20 MeV has been used in the following.
The primary positron distribution is generated with EGS4. The positrons are than tracked through the capture section with the program ASTRA. For the yield estimation additional cuts have to be applied in order to estimate the amount of positrons inside the transverse and longitudinal damping ring acceptance. In a real positron source these cuts have to be organized by adjustable collimators and appropriate beam optics. The purpose of the collimators is to match the positron distribution to the damping ring acceptance (especially in the longitudinal phase space) in order to minimize particle losses in the damping ring.
These cuts are done in somewhat different ways in publications of various authors and can hence not be directly comparable even if the level for the cut (e.g. the transverse acceptance) is the same!
After a brief comparison of the different cut criteria, yield calculations for conventional and undulator based positron sources will be presented.

## Longitudinal cut

In the longitudinal phase space the damping ring acceptance is limiting primarily in the energy spread but not in the bunch length. A long bunch gains, however, a large energy spread due to the curvature of the RF in the linac up to the damping ring. In order to limit the energy spread of the incoming positron beam one can hence either map the positron beam up to the damping ring energy and perform a pure energy spread cut [e.g. 10] or one can do an energy spread and bunch length cut at low energy [e.g. 9]. The bunch length in terms of RF phase corresponding to an induced energy spread $\Delta E/E$ is given as:

$$\Delta\phi = 2\arccos\left(1 - \Delta E/E\right)$$

Hence an energy spread of 1% corresponds to a bunch length of 10 mm and an energy spread of 2% corresponds to a bunch length of 14.7 mm.
In praxis a pure energy cut at high energy is easier to be realized but has the disadvantage of producing higher heat load and radiological problems. In addition some longitudinal cut at low energy might in any case be required in order to get rid of positrons in neighboring buckets. For the yield calculations both techniques yield similar results and cause no problem when comparing results.

## Transverse cut

Even though the solenoid-iris combination in the capture cavities presents a well defined transverse acceptance limitation, an additional acceptance cut is required afterwards to clean up the transverse phase space. This acceptance cut has to be related to the rms parameters of the positron beam since these will be used to match the beam into the damping ring. (More precisely the cut has to be related to the rms parameters after the cut, which requires an iterative procedure. The correction due to the iterations is however only small.) The position of an individual particle in phase space can be related to the rms ellipse by calculating the 'single particle emittance' of a particle as:

$$\varepsilon_i = \gamma x_i^2 + 2\alpha x_i px_i + \beta px_i^2$$

where α, β and γ are defined in the usual way via the rms properties of the beam.
The single particle emittance is up to the standard factor π equal to the area of an ellipse which has the same eccentricity and orientation in phase space (and the same offset in *x* and *px*) as the rms ellipse but has the point $x_i$, $px_i$ on its boundary.

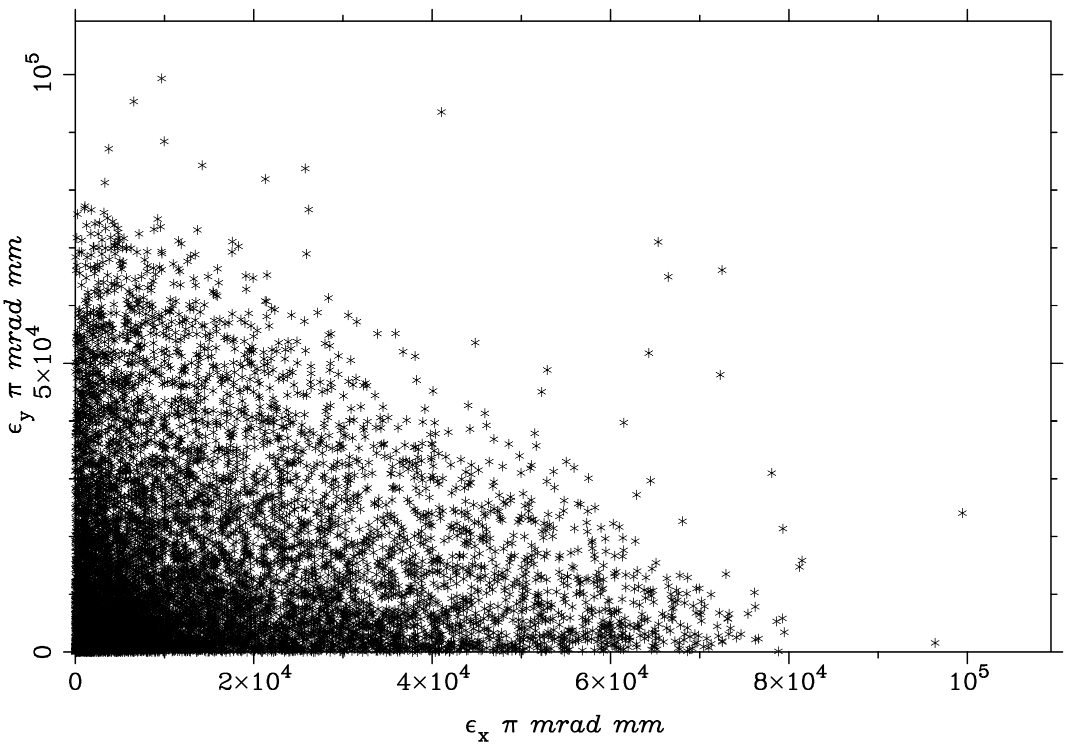


Figure 1: Vertical vs horizontal single particle emittance for a positron distribution after applying longitudinal cuts.

Figure 1 shows an example plot of the vertical vs the horizontal single particle emittance for a positron distribution after application of longitudinal cuts with a typical triangular shape and few particles far outside the main fraction of the positrons. The position of the diagonal boarder in the distribution depends on the solenoid strength $B_z$ and on the radius of the scraping aperture *R* and scales like: $B_z R^2$.

In order to clean up the phase space one can define a maximum emittance $\varepsilon_{max}$ and cut off all particles with $\varepsilon_{i,x} > \varepsilon_{\max}$ and $\varepsilon_{i,y} > \varepsilon_{\max}$. The phase space has then a well defined boundary and $\varepsilon_{\max}$ defines an edge emittance. The surviving particles form a square distribution in a plot like Figure 1.

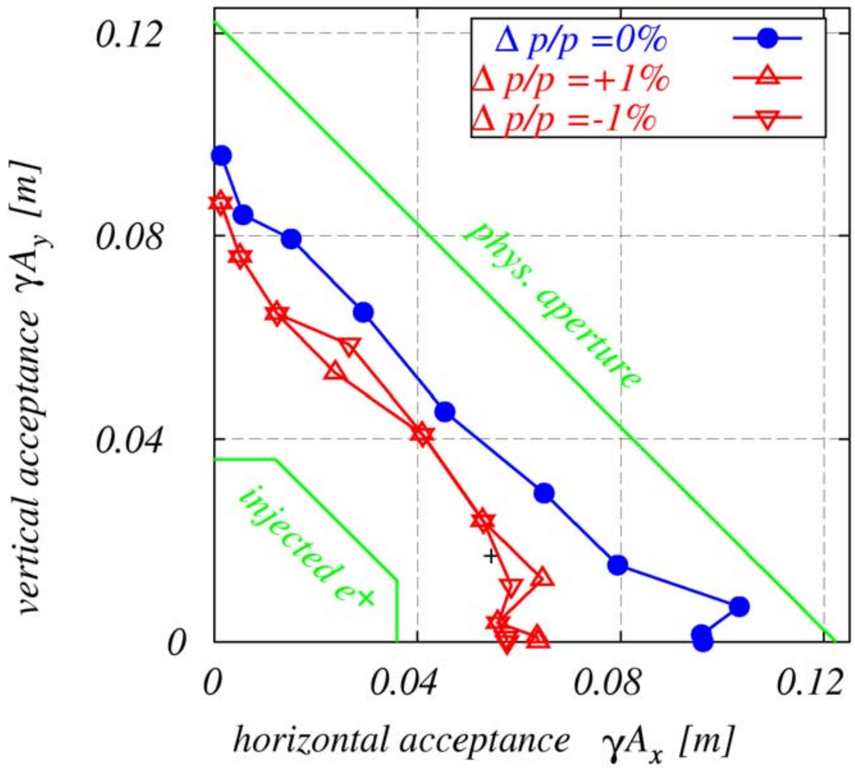


Figure 2: Acceptance plot for the TESLA damping ring [7]

Figure 2 displays as an example the acceptance of the damping ring as discussed in the TESLA TDR [7]. This plot suggests that a cut along a diagonal line in Figure 1 following the condition $\varepsilon_{i,x} + \varepsilon_{i,y} > \varepsilon_{\max}$ allows a better match of the positron distribution to the damping ring. Whether this argument is true for other damping ring designs is beyond the scope of this paper but it is obvious, that both kind of cuts lead to different results for the same edge emittance $\varepsilon_{max}$, as listed in Table 1. The primary positron distribution used for the simulations corresponds to the conventional source as described above. Before the transverse cuts a bunch length cut of 10 mm and an energy spread cut of ±25 MeV corresponding to a 1% energy spread at 5 GeV has been applied.

| | edge emittance rad m | rms emittance rad m | Capture efficiency % |
|---|---|---|---|
| square cut $\varepsilon_{i,x} > \varepsilon_{\max}, \varepsilon_{i,y} > \varepsilon_{\max}$ | 0.04 | 0.007 | 9.2 |
| diagonal cut $\varepsilon_{i,x} + \varepsilon_{i,y} > \varepsilon_{\max}$ | 0.04 | 0.0052 | 7.0 |

Table 1: Comparison of square and diagonal transverse cut.

The diagonal cut leads for *the same edge emittance* to a smaller capture efficiency and a smaller rms emittance. (It allows however to match a two times larger edge emittance into the damping ring acceptance of Figure 2.) Also the distributions of the horizontal and vertical phase space are somewhat different. While the square cut leads to a more uniformly populated phase space distribution, the diagonal cut leads to a more gaussian distribution with a dense core and some tails.

## Yield calculations for the conventional source

Figure 3 and Figure 4 present the calculated capture efficiency for the conventional source as described above. A solenoid field strength of 0.5 T and an aperture radius of the cavities of 23 mm [8, 9] have been assumed. The capture efficiency at the largest edge emittances displayed in the figures is limited by the acceptance of the solenoid-aperture section. If as large acceptances are achievable in the damping ring an even higher solenoid field might be considered. Assuming an energy acceptance of the damping ring of 1% the required capture efficiency of 11.5% is barely reached with the diagonal transverse cut at an acceptance of $\varepsilon_x + \varepsilon_y = 0.08$ rad m, while for the square cut $\varepsilon_x = \varepsilon_y = 0.06$ rad m is required.

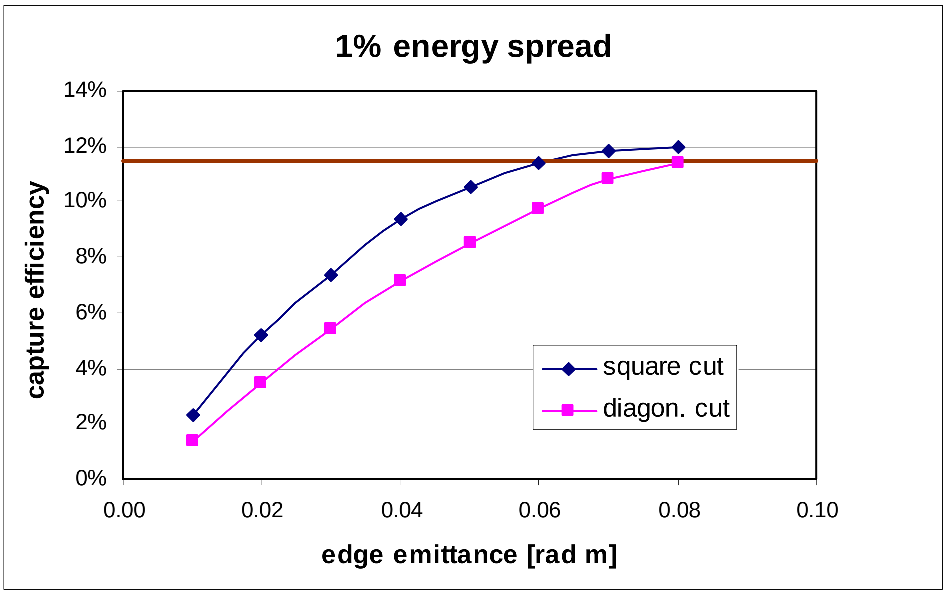


Figure 3: Capture efficiency vs edge emittance for a conventional source assuming 1% energy acceptance of the damping ring. The red line indicates the required efficiency for 1.5 positrons per electron at the damping ring.

While it is well known, that the dynamic aperture of a damping ring is reduced for off energy particles, a calculation assuming a larger energy acceptance can show the potential gain which might be realized by appropriate manipulations of the longitudinal phase space (e.g. bunching by deceleration or magnetic compression, linearization of the accelerating field).

The results shown in Figure 4 assume that the energy acceptance of the damping ring can be increased to 2%. A transverse acceptance of $\varepsilon_x + \varepsilon_y = 0.055$ rad m and $\varepsilon_x = \varepsilon_y = 0.04$ rad m is required for the diagonal and the square cut, respectively.

Figure 5 presents the rms emittance vs the edge emittance for a conventional source. The results depend not on the assumed energy acceptance, hence only the 1% energy spread data are shown.

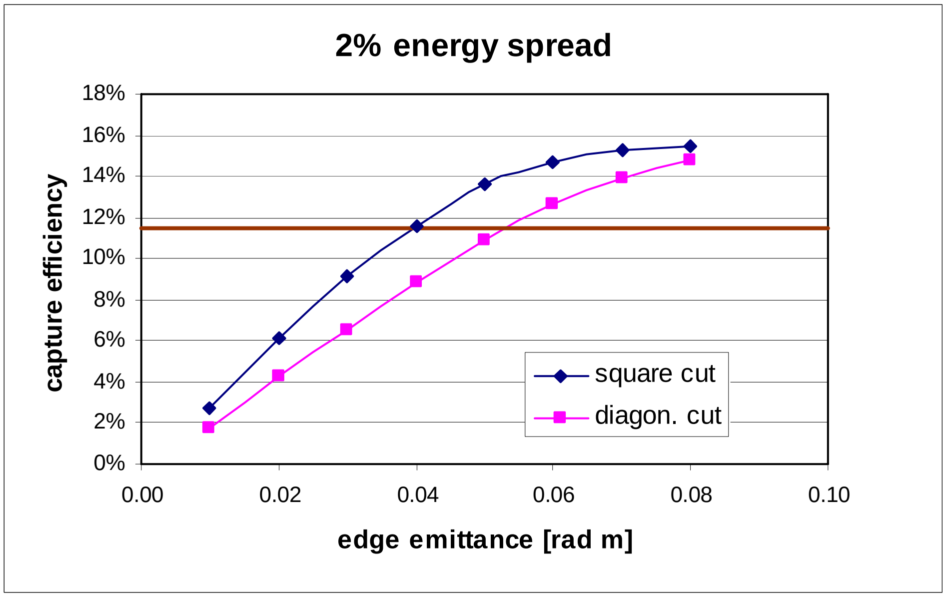


Figure 4: Capture efficiency vs edge emittance for a conventional source assuming 2% energy acceptance of the damping ring. The red line indicates the required efficiency for 1.5 positrons per electron at the damping ring.

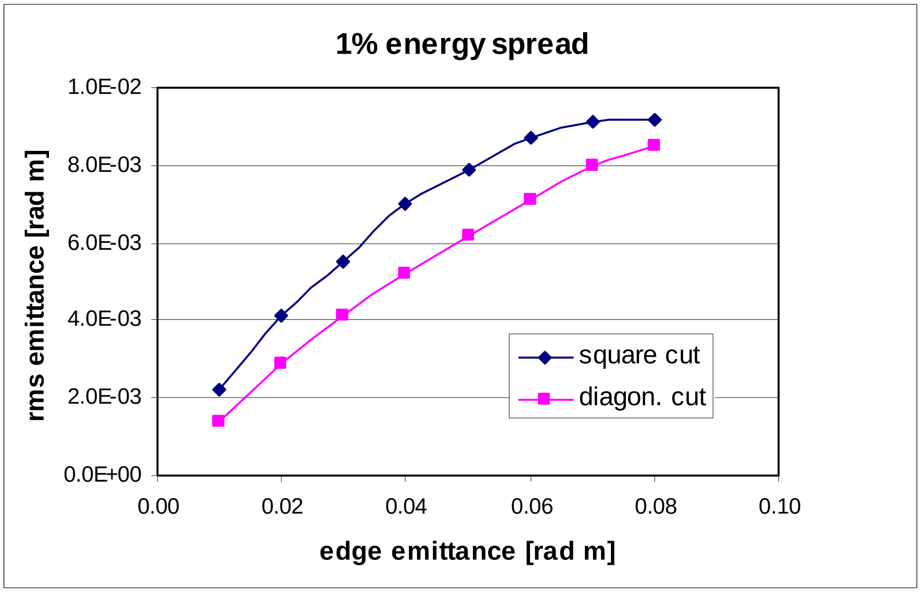


Figure 5: Rms emittance vs edge emittance for a conventional positron source.

## Capture efficiency calculations for the undulator based source

Figure 6 and Figure 7 display results for an undulator based source corresponding to the results of the conventional source displayed in Figure 3 and Figure 4. At the required acceptance values of the conventional source a capture efficiency above 35% is achieved, about a factor of 2 more than what has been typically assumed for the design of undulator based sources [3, 7-9].

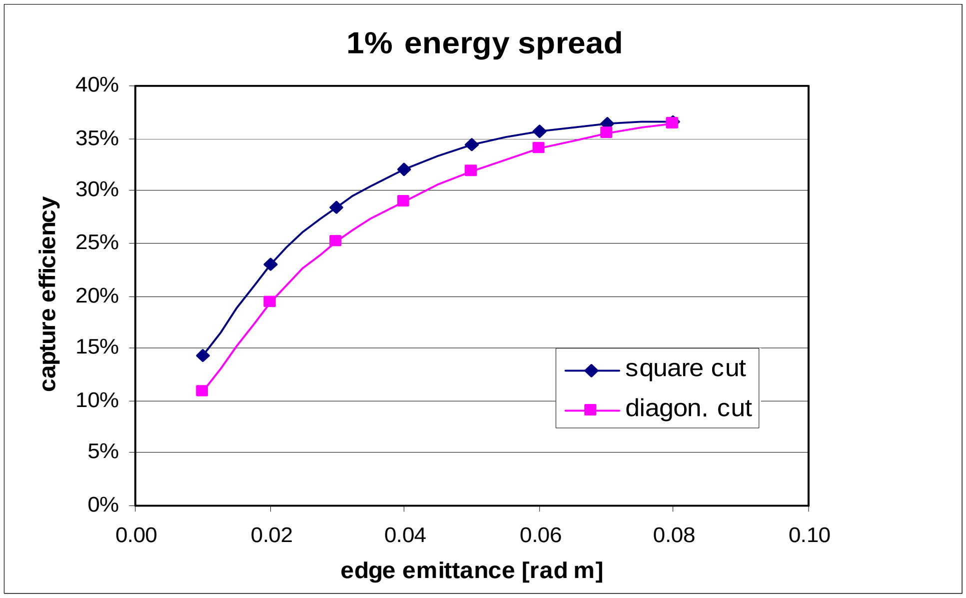


Figure 6: Capture efficiency vs edge emittance for an undulator based source assuming 1% energy acceptance of the damping ring.

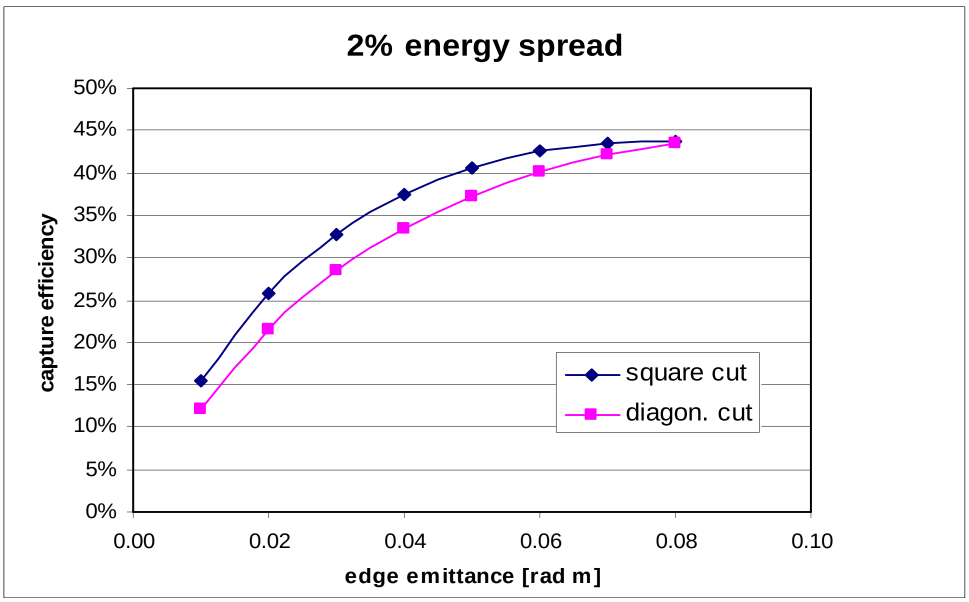


Figure 7: Capture efficiency vs edge emittance for an undulator based source assuming 2% energy acceptance of the damping ring.

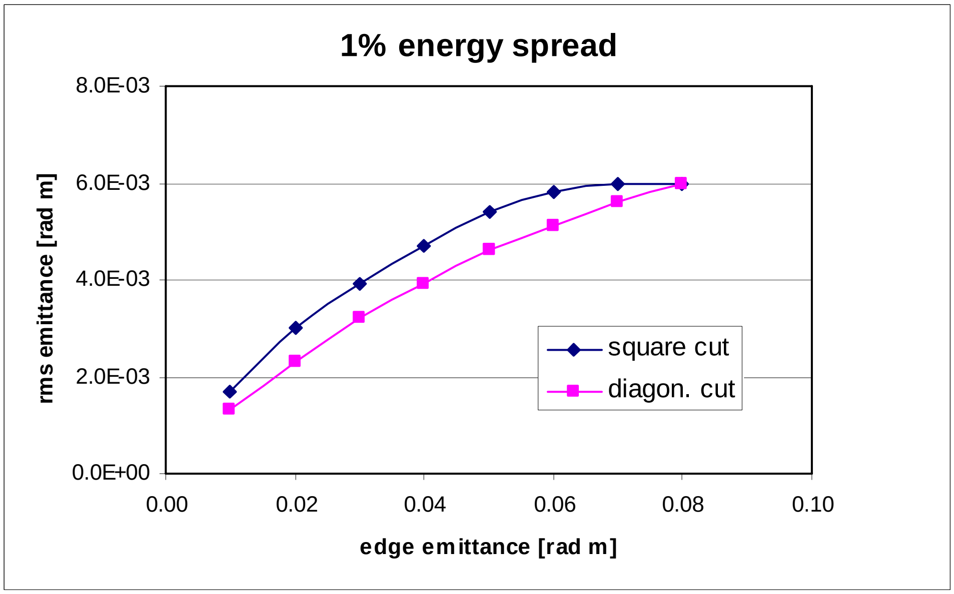


Figure 8: Rms emittance vs edge emittance for an undulator based positron source.

Figure 8 shows the rms emittance vs the edge emittance of an undulator based source which is in all cases lower than the corresponding emittance of a conventional source.
If the large acceptance required for the conventional source can be realized an undulator source can work with a short undulator (see below for details). The cost optimum might however be realized with a somewhat longer undulator and relaxed requirements for the damping ring. In case of difficulties with the damping ring design it is also conceivable to design an undulator based positron source for capture efficiencies as low as 10%. Thus depending on the achievable damping ring acceptance, the required undulator length, the energy loss of the electron beam, and the corresponding required linac length to compensate for this loss, and the energy deposition in the capture section can vary by a factor of up to 3.5, while the rms and edge emittance of the positron beam can vary by a factor of ~6-8.

## Energy deposition and neutron production

Undulator based positron sources and conventional sources differ fundamentally with respect to the energy conversion properties. While in a conventional source the power of the incoming electron beam is completely transferred to low energy particles in an electromagnetic cascade, only a small fraction of the incoming photon energy is transferred to charged particles in the thin target of an undulator based source. A large fraction of the incoming photon beam traverses the target unaffected and can be safely dumped in a photon beam dump in the case of an undulator based source, while the incoming electron beam power is completely deposited in the capture section and the target in case of the conventional source. In addition, the incoming photon beam power due to the better capture efficiency, is lower in the case of the undulator based source than the required electron beam power of the conventional source. Table 2 compares the incoming beam power and the power deposited in different parts of the positron source for the conventional source and an undulator based source.

| | **conv. source** | **undulator based source** |
|---|---|---|
| incoming beam power | 280 kW | 99 kW |
| yield | 1.5 $e^+/e^-$ | 1.5 $e^+/e^-$ |
| energy deposition: | | |
| target | 56 kW | 4.4 kW |
| capture section | 220 kW | 8.8 kW |
| electron dump | 4.9 kW | ~3 kW |
| photon dump | - | ~77 kW |

Table 2: Comparison of the energy deposition in the target and the capture section for the conventional and an undulator based source.

For this comparison the same damping ring acceptance as required for the conventional source has been assumed for the undulator based source, corresponding to a capture efficiency of 35%. However, even in case of a capture efficiency of 10-20% the power deposition in the target and capture section for the undulator based source is still significantly smaller than in the conventional source.

For the conventional source not only the high average heat load of the target is of primary concern but also the high load of the capture section. A large fraction of the 220 kW is deposited in roughly the first meter of the accelerating cavities following the target, thus substantially exceeding the load from the rf power. Therefore much stronger cooling of the cavities is required to keep mechanical deformations and rf properties (i.e. field amplitude and phase), under these conditions under control. Operational experience of cavities under such conditions does not exist and will be difficult to gain before building the ILC.

The high power deposition is accompanied by a strong neutron production. Detailed calculations are pending; however, first estimates show that the neutron production of the conventional source is more than an order of magnitude larger than in the case of the undulator based source [11].

The mechanical stress due to the high, pulsed heat load and the strong cooling (high flow velocities of the cooling water) and the larger neutron flux will have an impact on the availability and the cost of the conventional positron source which needs further consideration.

Activation and radiation damage of the target and other elements of the capture section are an issue for both kinds of sources. Radiation hard magnet and cable insulation and local shielding will be required in sections close to the target. Accessibility of these sections for maintenance and repair will be limited, remote handling capabilities might be required.

Concerning the beam line elements of the capture section the problems are reduced due to the lower neutron production in case of the undulator based source. However, the preferred target material for the undulator based source is Titanium, which has a lower threshold displacement energy for defect production as Tungsten [12][1]. The impact of atomic displacements on the mechanical properties of a material are, however, not trivial and depend on e.g. the chemical composition of the alloy, the neutron energy, and the temperature of the irradiation. A Titanium alloy for applications in nuclear power plants (named RK-20) has been developed and the effect of neutron radiation on the mechanical properties has been studied in detail for a number of alloys [14, 15]; the applicability of these results on the target problem needs to be understood. An interesting feature of the investigated Ti-alloys is the temperature dependence of the radiation effects. Above 300°C irradiation temperature the RK-20 alloy ‘virtually passes to the class of materials with a weak susceptibility toward radiation embrittlement’ [14]. Whether the pulsed temperature rise due to the power deposition of the photon beam is sufficient to take advantage of this effect or an additional increase of the average target temperature is required needs to be investigated. Another advantage of the RK-20 alloy is its low induced radioactivity after irradiation.

A further reduction of the radiation damage can for both kinds of sources quite easily be realized by moving the incoming beam slowly over different parts of the target [5].

The mechanical properties of Titanium alloys are excellent and the safety margin of the induced stress to the yield limit is larger in case of the undulator based source as compared to the conventional source [5, 16, 17]. A further increase of the safety margin is possible by increasing the target size and/or the rotational speed of the target. This allows an operation also in case of radiation damage of the target. For the conventional source this possibility is limited and the stress turns out to be close to the fatigue limit.

## Placing the undulator at 150 GeV or at 250 GeV (end of the linac)

Two proposals have been made concerning the positioning of an undulator based positron source. In [7] the undulator is placed at the end of the electron linac and integrated into the BDS design. In this way the operation of the linac at various energies is not affected but the operation of the positron source depends on the c. m. energy requested by the users. The proposal in [2] foresees to place the undulator in the middle of the linac at about 150 GeV. Since the linac energy at this point should be kept fixed so that the source operation becomes independent of the c. m. energy, only the second part of the linac is available for the energy variation and hence the linac operation is affected. In the next paragraph the required undulator length for the operation in the energy range of 150 GeV and 250 GeV will be specified before discussing the strategies for the operation below 150 GeV and above 250 GeV.

---

[1] The required photon number for the positron production is overestimated in reference 5. Reference 12 concludes 13 DPA (Displacements Per Atom) for a photon dose of $1.86\cdot10^{27}$ photons per square meter, predominantly produced by neutrons. With the parameters used in this report (target diameter, photon beam spot size and undulator parameters) only $1.23\cdot10^{26}$ photons per square meter are accumulated in one year of operation at 250 GeV operation energy, corresponding to 0.86 DPA. This is the worst case, since at 150 GeV ~3 times more photons are required but the photon energy is below the giant neutron resonance. Assuming that the photons in reference 12 are all started with an energy of 22 MeV (this needs to be clarified, the report is not precise concerning this point), i.e. on the giant neutron resonance, while in reality only a fraction of the photon spectrum overlaps with the giant resonance it appears, that the Titanium target for the undulator based source will have similar DPA than the corresponding Tungsten target of a conventional source (0.33 DPA per year, scaled from [13]).

## Required undulator and linac length

The required undulator length depends on the undulator parameters, the capture efficiency (i.e. the damping ring acceptance) and the electron beam energy. Table 1 presents results for two different helical undulators. Helical undulators are necessary if polarized positrons shall be produced, but offer the additional advantage of producing more photons per unit length as planar undulators of comparable strength. Undulator I assumes parameters as proposed by the Daresbury group, Undulator II assumes more aggressive parameters in order to demonstrate the development potential. For the purposes of comparison a capture efficiency of 35%, corresponding to the large damping ring acceptance as required for the conventional source, has been assumed. A cost and performance optimization might lead to a smaller damping ring acceptance and correspondingly longer undulators.

If the undulator is installed at the end of the linac, the undulator length required for the operation at 150 GeV still needs to be installed (but not operated at the higher electron beam energies, see below). Concerning the required additional linac length the loss at 250 GeV is relevant since at low gradient operation sufficient energy is available. The difference is however marginal. So what are the advantages of an installation at the end of the linac?

The most obvious advantage is the additional reserve in the positron yield (~factor of 3). In case of problems, e.g. with the dynamic acceptance of the damping ring (a problem that is likely to occur in the beginning of the operation) this reserve can be used to reduce the emittance of the injected positron beam, while keeping the beam intensity constant. In view of the great challenge ILC, the little experience with comparable machines and the many things which might work a little bit different than expected a tremendous advantage.

| | **Undulator I**<br>B = 0.75 T, λ = 1.2 cm, K = 0.84 | | **Undulator II**<br>B = 1.27 T, λ = 1.1 cm, K = 1.3 | |
|---|---|---|---|---|
| elec. energy | 150 GeV | 250 GeV | 150 GeV | 250 GeV |
| undu. length | 143 m | 42 m | 50 m | 17 m |
| energy loss | 2.3 GeV | 1.9 GeV | 2.3 GeV | 2.2 GeV |
| $E_1$ | 10.4 MeV | 29 MeV | 7.2 MeV | 20 MeV |

Table 3: Required undulator length to produce 1.5 positrons per electron and energy loss of the electron beam for two undulators and two electron beam energies. $E_1$ is the energy of the first harmonic of the radiation of the undulator, the K-value is proportional to the product of undulator period λ and magnetic field *B* and characteristic for the content of higher harmonics in the radiation spectrum.

Secondly, the additional photons can be used to improve the positron polarization. To produce positrons with a high polarization it will be required to scrap off-axis photons off since only the on-axis photons are fully circularly polarized. In order to produce highly polarized positrons at 150 GeV the undulator length needs to be increased which requires additional investments. It needs to be discussed which polarization level at which beam energy should be realized. An obvious scenario would be to start with an undulator length which allows only a modest positron polarization at 150 GeV and gain experience with the production of highly polarized positrons at 250 GeV before installing additional undulator segments.

With the undulator installed at the end of the linac the positron yield drops below the design value of 1.5 positrons per electron and will affect the luminosity when the c. m. energy is reduced below 150 GeV. When the luminosity drops by a factor of 2 the operation mode is changed.[2] Pulses for the generation of luminosity are produced at half the rep rate and every other pulse is used for the positron production. This operation mode requires a bypass line. Hence no energy gap exists (as stated in [2]) but the luminosity is reduced by a factor of 2 at lower energies.
The possibility to add a second injector in order to use a fraction of the linac for the production of luminosity while the rest is used for positron production is a specific upgrade option for a possible high luminosity operation on the Z-pole (Giga-Z). For calibration runs on the Z-pole the intensity of the auxiliary positron source is sufficient.
Since the power consumption and the beam loading are reduced when operating at lower gradients other upgrade options as increasing the current or the rep rate might be considered if interesting physics is discovered in this energy range. These options might however be limited by other subsystems as the damping ring.
When the linac is upgraded to reach c. m. energies above 500 GeV the energy of the undulator photons is further increased and the required undulator length is reduced. The source can be operated up to 1 TeV c. m., however, the efficiency of the positron production is reduced at higher energies since the photon energy increases while the pair production cross section stays constant. At 500 GeV electron beam energy only 8 m of undulator are required but the energy loss of the electron beam is 4 GeV. Hence it is desirable to exchange the undulator at some point to recover efficiency. An important constraint is the separation of the photon and electron beam without emittance dilution at high energy. Additional length can be gained when the undulator is exchanged (or sections are removed) since only a short undulator is required.

When the undulator is installed at the 150 GeV point it is proposed to decelerate the beam after the positron source in order to reach c. m. energies blow 300 GeV. The energy jitter and the emittance dilution will increase while the beam is decelerated. Options to improve the beam quality for very low c. m. energies by adding a second injector and a bypass line e.g. for a high luminosity Z-pole operation exist, however, also in this case.
The impact of this option on the beam dynamics and linac operation needs to be understood. Already at c. m. energies above 150 GeV the linac has to be operated with half the machine running at full power, while in the other half many components, especially of the rf system, have to be operated far from there nominal settings. It is not obvious that all components work with the required stability when operated under these conditions. Beneficial effects of a low gradient operation (reduced power consumption, reduced failure rate of components) are limited to the second half of the linac. The tuning time requirement after a variation of the energy is likely to be higher for the very low

[2] With the undulator parameters specified in Table 3 this will happen between 100 and 120 GeV electron beam energy.

gradient and deceleration mode of operation in comparison to the case where the complete linac can be used to adjust the energy. Details have not been worked out yet.
The position of the undulator can not be moved when the linac is upgraded to reach c. m. energies above 500 GeV since it requires large underground buildings. To keep the energy at the source location fixed would require fixing the upstream gradient at a very early stage which is not compatible with all upgrade scenarios. Some variation of the beam energy has therefore also in this case to be expected and taken into account in the design.

## Operation

The argument to place the undulator in the linac at the 150 GeV point and operate it with a fixed energy is that the source operation becomes in this way independent of the c. m. energy requested by the users. Considering a static situation it is agreed, that the positron source can be designed to operate at both points. The undulator for both sources can be assumed to be the same, so that the source at the end of the linac can also be operated down to 150 GeV beam energy. In this case it is obvious, that operation of the source at the end of the linac gives additional flexibility with respect to the positron yield and/or positron emittance when the linac is operated at energies above 150 GeV, because the positron yield increases with increasing electron energy. The argument in favor of the source at the 150 GeV point is relevant only in the dynamic case when the c. m. energy of the linac is changed. A number of questions have to be addressed before judging about the relevance of this argument:

1. How often needs the linac energy to be changed? Will it change on a daily, weekly, monthly or yearly basis and will these changes be in the form of rather small steps which the operational tuning will quasi adiabatically follow or will large steps in the c. m. energy be requested? Questions which are clearly beyond in the scope of this note. It is however obvious, that we can not discuss operational questions without any vision of the possible operational requests of the users.
2. How much time does it take to change the linac energy and tune it back to full luminosity? How much additional time does it take if the source is located at the end of the linac?
3. Does the linac tuning become more difficult by the restriction that the c. m. energy can be changed only by the second part of the linac in case that the source is located at the 150 GeV point? How much time does this cost?

Question 1 requires input from the users. Without detailed discussion it seems to be obvious, that in case of gradual energy variations on a rather long time scale the additional tuning for the source located at the end of the linac will be hardly distinguishable from the day-to-day tuning effects (i.e. small luminosity variations) and that question 2 and 3 become relevant in case of larger energy steps on a shorter time scale.
In order to address question 2 some understanding of the source is required as which parameters need/can be tuned in order to optimize the positron yield, how sensitive the positron yield depends on these parameters and which parameters need to be adjusted if the electron energy is changed.

## How can the intensity of the positron beam in case of an undulator based source be adjusted

In order to adjust the intensity of the positron beam one can either modify the capture efficiency of the optics downstream of the target or one can change the intensity of the photon beam used for the positron production.

For a modification of the capture efficiency one can change e.g. the solenoid field strength in the capture section or adjust the setting of the collimators. However, it is preferable to adjust the capture optics once for maximum capture efficiency at minimized losses in the damping ring and keep it further on fixed. In this case the emittance and orbit of the positron beam remains basically unchanged when parameters upstream of the collimator section are changed and tuning efforts downstream of the collimator section are minimized.

In order to change the intensity of the photon beam sections of the undulator need to be switched on or off. A fine tuning below the granularity of the undulator sections can be done by a variation of the undulator field. A permanent magnet undulator requires opening the gap for this. In case of a planar undulator a simple transverse motion would also be possible to switch sections of. Undulators with adjustable gap are common in synchrotron radiation applications and are also proposed for FELs with undulator length and requirements on alignment tolerances beyond what is required for the positron source. For a superconducting helical undulator it would of course be straight forward to switch individual sections off.

## Sensitivity of positron beam parameters

A detailed sensitivity study is beyond the scope of this paper and requires in any case a fully designed beam line including collimator sections which is not yet at hand. Positron beam parameters as the beam emittance, initial optical functions and beam offsets, energy and energy spread are to a large extent determined by the fixed collimator settings. Variations of the position and the average positron beam energy in front of the collimator section are a source of parameter variations which should be minimized by orbit and energy feedback systems. Assuming appropriate collimators and feedback systems located at low beam energy the impact of parameter variations in the target and capture section on the beam properties downstream of the collimator section are minimized and can be described by a variation of the charge and the rms emittance of the positron beam.

Hence only the first section of the source, starting at the target is considered in the following. The same parameters as in the previous sections have been assumed for the photon beam and capture section and cuts have been applied corresponding to a 1% energy and $\varepsilon_x + \varepsilon_y = 0.04\,\mathrm{rad\,m}$ transverse acceptance of the damping ring. For this transverse acceptance a smaller solenoid field would be sufficient. Operation with the higher solenoid field leads to a larger load on the collimators but reduces the sensitivity of the capture efficiency on parameter variations and field imperfections.

Important parameters which have an influence on the positron yield and emittance are the position and size of the incoming photon beam on the target and the amplitude and phase of the first rf section in the capture section. The tuning and stability of the static solenoid field setting seems to be uncritical and will not be discussed here. The stability of a pulsed solenoid field as it might be required for the first part of the matching section is certainly critical and needs to be discussed together with the technical design.

| | | charge variation | rms emittance variation |
|---|---|---|---|
| electron beam energy | ± 1 % | ± 2 % | ± 0 % |
| incoming photon beam spot size | + 30 % | - 1.1 % | + 2 % |
| photon beam off-set | ± 0.5 mm | - 3.5 ‰ | ± 0 % |
| rf phase of the first capture section | ± 5° | - 2.6 ‰ | ± 0 % |
| rf amplitude of the first capture section | ± 5 % | ± 0.7 ‰ | ± 0 % |

Table 4: Sensitivity of positron beam parameters on selected parameters of the incoming photon beam and capture section.

The positron beam size at the target exit is given by a convolution of the incoming photon beam size[3] and the beam size formation due to the scattering in the target. In case of the undulator based source the scattering process is the dominating factor, which leads to the low sensitivity of the yield and emittance on the position and size of the photon beam. The bunching process depends only weakly on the phase of the first cavity as one might expect. These results are only preliminary and need to be extended once the design has been fixed in more details. Nevertheless it seems to be justified to assume, that a stable operation with a minimum of tuning can be realized with a proper design of the capture and collimator section.

## Tuning requirement after change of energy

When the energy of the electron beam is changed, also the energy of the undulator photons changes. Due to the energy dependence of the pair production cross section the yield changes and the active undulator length needs to be adjusted. The required undulator length is to a high degree predictable.
The variation of the undulator length has a small impact on the dynamics of the electron beam since the energy and the energy spread change. A relatively fast and automatic correction of the electron beam energy will in any case be required to deal with failing rf stations. The energy variation should hence be automatically corrected. The impact of steering effects of the undulator can also be automatically corrected if they are significant. The induced energy spread is predictable and should cause no significant problem.
The variation of the photon energies causes a variation of the positron energies emerging from the target. The first part of the capture section forms a broad band focusing optics

[3] The photon beam size is dominated by the natural divergence of the photon beam. This is an inherent safety feature since the target can not be destroyed by a wrong setting of the electron beam. In case of the conventional source the incoming electron beam spot size needs to be continuously and nondestructive measured and interlocked.

for the positrons. The solenoid settings are independent of the photon and positron energy, respectively. Also the phases of the cavities which are responsible for the longitudinal capture need no adjustment. The beam energy at the end of the capture section changes by ~ 6 MeV when the electron beam energy changes from 150 GeV to 250 GeV due to the difference in the positron energies at the target. In front of the energy collimator this needs to be corrected by the energy feedback system; sufficient reserve in the rf systems should be provided. With fixed collimator settings the edge emittance of the beam stays constant. The rms emittance changes by about 3% in the simulation (limited by statistics). As in the previous section these results have to be considered as preliminary. Extensions need to be done once more details of the design have been fixed. With these precautions it can still be concluded that the tuning effort in case of a variation of the energy is small and manageable. Possibilities for automatic corrections are obvious and can rather easily be implemented.

## Commissioning

The necessity to run the main electron linac for the generation of positrons is a disadvantage of the undulator based source concerning the commissioning of the source itself but also concerning the commissioning of the positron damping ring and the positron main linac.

On the other hand, a conventional positron source requires additional commissioning work for the drive linac and has to be well tuned to reach the design parameters, while the ability to produce a larger amount of positrons into a smaller phase space volume, especially when operated at higher electron beam energy, simplifies the commissioning of the positron source and downstream components in the case of the undulator based source. It is conceivable to start operation with closed collimators using the undulator overhead and improve on this when the damping ring acceptance is improved by better tuning. Moreover should a significant fraction of the commissioning of the positron damping ring also in case of a conventional positron source be done with electrons since the much smaller phase space volume of the electron beam will ease the commissioning work significantly. The possibility to extend the commissioning with electrons above what would also be done in case of a conventional source and the possibility to use the required electron source for the production of a low intensity positron beam mitigates the disadvantage of the linked operation of the undulator based source. It will be important to keep this auxiliary source on the level of a small add-on, which is well integrated into the design of the undulator source so as to not obscure these arguments. In [7] it is proposed to use a ~500 MeV electron source which can be directed onto the target of the undulator source as auxiliary source. Besides a full spec electron beam this source could deliver a positron beam of ~1% intensity with the standard bunch structure without any modification of the capture optics. Since the undulator target and capture optics would be used the positrons could be used for the commissioning of these sections and would have an emittance and orbit practically identical to the positron beam produced with the undulator; a significant advantage compared to other, more complex scenarios. A stand-by operation of the electron source can easily be realized so that a fast switch to the auxiliary source would be possible. It has to be understood in how far modifications of the beam diagnostics would be required for the low beam intensity to become useful.

Another possibility to be explored is whether it would be possible to accumulate positrons in the damping ring in order to produce a beam of higher intensity and low rep rate for study purposes.

It is obviously difficult to quantify the commissioning time required for the different options. It is generally accepted that an early commissioning of parts of the machine already during the construction phase would be beneficial, even though we have no agreement whether commissioning in this case means just extended system tests or already running up to full specs. Commissioning during construction should in any case not compromise the installation schedule. Given that the same people responsible for the commissioning of a machine section are also involved in the design and take responsibility for the construction of the machine the possibilities to commission the electron and the positron side of the machine in parallel, as it would in principal be possible in case of a conventional positron source, might be limited just by available person power. Given that the construction and commissioning of the ILC in terms of person years is roughly independent of the chosen positron source option and that the same person power is available, the total time required seems to be more a question of appropriate planning and scheduling than of anything else.

## Cost

The cost of the positron source is of second order in the sense that a cheaper source does not help if it does not achieve the requested performance. A detailed cost comparison can not be done at this point, however, some general comments can be made.

For the undulator based source, the required undulator, linac and tunnel length is independent of the source location. Some length difference exists in the additionally required length for the electron beam extraction. An undulator based source at the end of the linac can, however, be integrated into the design of the beam switch yard and the machine protection system. A cost reduction can be achieved since e.g. buildings which are required for the switch yard can also be used for the positron source, while separate buildings are required in case of an installation at the 150 GeV point. The efficiency of this cost reduction depends on the detailed switch yard design.

The cost comparison in [2] yields a 2% difference between an undulator based source located at 150 GeV and a conventional positron source. However, the assumed undulator parameters result in an energy loss of 4.9 GeV (unpolarized) and 6.5 GeV (polarized) and the required additional linac and tunnel length to compensate for this are a significant cost contribution. (The conventional source is based on a 6.2 GeV linac.) These parameters are not compatible with the acceptance requirements for the conventional source. A cost difference in the damping ring design or a pre-damping ring is, however, not accounted for. If the damping ring acceptance required for the conventional source can be achieved only ~2.5 GeV (unpolarized) and the corresponding tunnel length will be required for the undulator based source (Table 3)[4], thus the undulator based source becomes significantly cheaper. A cost optimization of the positron source – damping ring system can be performed for the undulator based source. If the damping ring acceptance can not be achieved and a pre-damping ring is required the conventional source becomes

[4] The required undulator length will also be shorter by a factor of 2 for the same undulator period and field. The achievable fields and periods are, however, not fixed yet and the assumed length of 150-200 m is not unrealistic.

significantly more expensive. In any case the undulator based source at the end of the linac appears to be the cheapest solution although this needs to be quantified.
The polarized positron source option requires additional undulator, linac and tunnel length but it also has a value in it own which can not be achieved with the conventional source. Hence these additions should be accounted for separately.

## Conclusion

The undulator based positron source has the highest performance in terms of beam quality (yield, emittance) and a large extra reserve in the production rate especially when operated at the end of the linac. It has the lowest power deposition in the beam line components, the lowest neutron production and the largest safety margin w.r.t. the mechanical stress in the target. Radiation damage in the target is of comparable order than in the conventional source and radiation hard Titanium alloys might improve this situation further.
These features allow for a cost optimization of the positron source – damping ring system and give a high flexibility to adjust the beam parameters in case of unforeseen problems but also to new requirements (e.g. higher currents, different pulse structures) which might come up during the long operation time of the ILC.
The obvious disadvantage of the undulator based source is the linked operation with the main electron linac. This is predictable and can be mitigated by appropriate scheduling and a small auxiliary source. The great reservations against a linked operation are to a large extent based on experience with the SLC positron system. One of the identified problems of the SLC positron system was that it formed a feedback loop in which the intensity of one bunch had an influence on the production rate of the next bunch [18]. This problem will not exist at the ILC. The main problem was however, that the SLC positron source was limited in yield. To produce a sufficient positron intensity required to make full use of the available acceptance of the transport lines and damping ring, which required a fine tuning of many parameters. With a higher yield it would have been possible to design and operate the source in a more stable parameter regime. The conventional positron source for ILC has the same problem. The large acceptance requirement (Figure 3 and Figure 4) is beyond achieved values in damping ring designs. The required yield seems only to be achievable with an additional pre-damping ring or additional manipulations of the longitudinal phase space. In addition is the conventional source constrained w.r.t. the mechanical stress in the target and the power deposition in the capture section. Even with a pre-damping ring or other means to increase the capture efficiency will it be necessary to achieve all parameters close to 100% to make a conventional positron source for ILC work. (Note that the calculations so far have been done with ideal fields and without errors.) This requires a fine tuning of many parameters and increases the sensitivity to parameter variations. The limitation in yield represents a considerable risk for ILC.
For the purpose of a fair comparison the same acceptance as required for the conventional source has been assumed in this note for the undulator based source, corresponding to a capture efficiency of 35%. More realistic assumptions result in a capture efficiency of about 17%. (This might be improved, as in case of the conventional source, by additional manipulations of the longitudinal phase space. A pre-damping ring would certainly not be cost effective for the undulator based source.) Correspondingly the required undulator

length (Table 3) and the power deposition (Table 2) will be about 2 times larger. The impact on the cost and the performance of the damping ring design will however be much smaller in case of the undulator based source. Additional undulator length is required if the positron beam should be polarized.
Depending on the achievable undulator parameters a high polarized positron production is questionable at 150 GeV operations. Further R&D to improve the achievable undulator parameters is necessary.
The installation at the 150 GeV point simplifies the operation of the positron source, but limits its flexibility and parameter range (e.g. max. polarization). The cost of this source is higher than an undulator based source at the end of the linac. Furthermore has this option a strong impact on the linac operation. It limits the efficiency of the linac operation at lower gradient, the flexibility and might impact the upgrade scenarios. These impacts are not studied in detail and it is questionable whether the tuning requirement for the source operated at the end of the linac justifies these complications.

## References


1. E. Elsen, “ILC Source Reliability”, N. Phinney, “ILC Availability Simulation ─ An Update with Concentration on $e^+$ Sources”, Workshop on Positron Sources, Daresbury, Apr. 05.
2. U. S. Linear Collider Technology Options Study, Mar. 04, http://www.slac.stanford.edu/xorg/accelops/
3. K. Floettmann, “Investigations toward the development of polarized and unpolarized positron sources for linear colliders”, DESY 93-161, Nov. 93.
4. J. Sheppard, “Conventional Positron Target for a TESLA Formatted Beam”, LCC-133, SLAC-TN-03-072, Nov. 03.
5. W. Stein, “Conventional and Undulator Beam Target Thermal-Structural Analyses”, Workshop on Positron Sources, Daresbury, Apr. 05.
6. W. Stein, “Structural Modeling of TESLA TDR Positron Target”, LCC-0089, UCRL-ID-148939, July 02.
7. TESLA Technical Design Report, Part II, Mar 01, http://tesla.desy.de/new_pages/TDR_CD/start.html
8. V. Balandin et al. “Conceptual Design of a Positron Pre-Accelerator for the TESLA Linear Collider”, TESLA 99-14, Aug. 99.
9. V. Balandin et al. “Conceptual Design for a Positron Injector for the TESLA Linear Collider”, TESLA 2000-12, July 00.
10. Y. Batygin, “Positron Collection in the ILC”, Workshop on Positron Sources, Daresbury, Apr. 05.
11. S. Riemann,”Radiation Aspects in Positron Sources”, Workshop on Positron Sources, Daresbury, Apr. 05.

12. M.-J. Cartula et al. “Report on Radiation Damage Effects in a Titanium Target under Photon Irradition”, UCRL-ID-149951.

13. M.-J. Cartula et al. “Radiation Damage Induced by GeV Electrons in W-Re Targets for Next Generation Linear Colliders”, LCC-0093, UCRL-JC-148049, July 02.

14. O. A. Kozhevnkov et al. “Mechanical Properties, Fine Structure, and Micromechanisms of Fracture in Titanium α-alloys Irradiated with Neutrons”, Metal Science and Heat Treatment, Vol. 41, Sep. 99.

15. O. A. Kozhevnkov et al. “Influence of neutron irradiation on deformability and fracture micromechanisms of titanium α-alloys”, Journal of Nuclear Materials 271&272, 1999.

16. W. Stein et al. “Structural Modeling of TESLA TDR Positron Target”, LCC-0089, July 02.

17. W. Stein et al. “Thermal Stress Analyses for the NLC Positron Target”, LCC-0088, July 02.

18. P. Krejcik, “A Simple Model for the SLC Positron Stability Issues”, SLAC-PUB-5725, Jun 92.