Prototypes and R&D for undulator-based positron sources

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Abstract. The undulator-based positron source is baseline design for the ILC. Recent progress in particular on the undulator mask designs, optic matching devices (R&D for prototypes for pulsed solenoid, plasma lens) and on the target design (rotating wheel, material tests) are discussed. The adaption of an undulator-based positron source for the HALHF design as an upgrade option for the ILC is included as well.

1 Overview

The most advanced design for a future e^+e^- linear collider (LC) with a first stage centre-of-mass (cms) energy of 250 GeV (ILC250), followed by the stages of 350 GeV and 500 GeV and upgradeable up to 1 TeV is the International Linear Collider (ILC) using superconducting RF cavities. Already in its ILC250 stage it provides already high luminosity of about $\mathcal{L} = 0,75 \times 10^{34} cm^2 s^{-1}$ [1]. As for all LC designs, the positron device is demanding, and the ILC used the mature design of an undulator-based e^+ source as baseline design, providing even polarized positrons that are required to fulfill all envisaged physics and precision goals [2–4]. The layout is shown in Fig. 1: the e^--beam of 125 GeV is led through the superconducting helical undulator, generating circularly-polarized photons of about 7.5 MeV that produce in the thin (7mm for ILC250 and 14 mm for ILC500) Ti-Alloy target polarized e^+ (and e^-). The e^+ are captured, pre-accelerated and led through spin rotators before entering the damping ring.

2 Ongoing work within International Technology Network (ITN)

The high-intensity e^+-source, providing about a factor 100 more positrons per second than the positron source of the former SLC, has still some R&D engineering issues to solve. The next steps towards a full feasible design for the ILC are undertaken now within the International Technology Network (ITN) . These are mainly the positron target, the rotating wheel and the capturing devices. The optimization and protection of the undulator system, in particular for the undulator most challenging stage of cms=250 GeV, has been studied as well. In the following a short summary about the ongoing progress and recent results are given.

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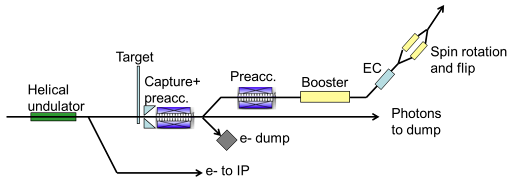

Figure 1. Outline of the undulator-based positron source for the baseline design of the ILC [1].

2.1 Undulator field simulations and mask system

Advanced simulations of the undulator have been performed [5], i.e. probing the impact of field misalignments and taking into account errors in the magnetic field (K-value) and the period λ. Depending on the K-value, such uncertainties have impact on the polarization and on the target load. Furthermore, in [5] also a mask system to protect the undulator walls has been studied, see Fig. 2. With such masks, the synchrotron radiation deposit is kept under the level of 1 W/m. With such a mask system the power deposition in the 'last' mask near the undulator exit, that gets the strongest load, is expected to be at about 300 W.

In Fig. 3 (left panel) the energy deposition is shown for different mask materials (Cu (blue), W (orange)) and compared with both an ideal mask (green) as well as no masks (black). It can be seen that without a mask system the limit of 1 W/m (red line) is reached already after about 120 m. However, including the masks the undulator are well kept below such a level even at the maximal full length of 320 m.

The simulations have also been done for the other cms energy stages of 350 GeV, 500 GeV as well as for GigaZ. The ILC250 GigaZ option will run with an 2×3.7 Hz scheme for the e^- beam, alternating a 125 GeV undulator drive beam and a 45.6 GeV collision beam [6]. Since the incident power on the wall is at GigaZ comparable or below the incident power at ILC250, see Fig. 3 (right panel), the implement such a proposed mask system will also be sufficient for the GigaZ option. Therefore the implementation of such a mask system is absolutely substantial, more details can be found in [5].

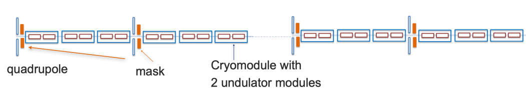

Figure 2. Mask System to protect the undulator walls from synchrotron radiation below a level of 1 W/m[5].

2.2 Target Material Analyses

At the Mainz Mikrotron MAMI several ILC target tests have been performed: the electron beam hits on the target material (Ti-alloy, W), generating the same cyclic load with the same/even higher peak energy deposition density (PEDD) as expected in one year running at the ILC. The materials have been analysed afterwards with several scanning [7] method and diffraction [8] methods.

The ILC target Ti-alloy has two different material phases, α and β, that have different material properties. Depending on the temperature the impact of the different phases can be

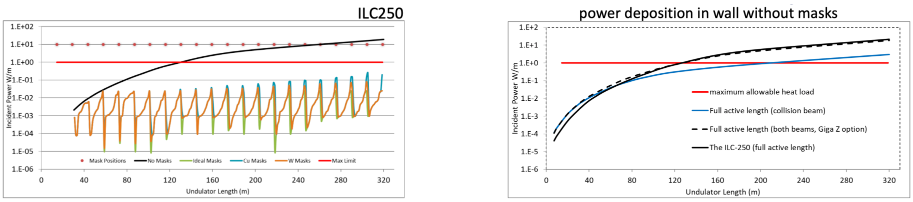

Figure 3. Left: Incident power on the undulator walls w/wo mask system for different mask materials for the ILC at $\sqrt{s}$ = 250 GeV [5]. Right: Power deposition without the mask system for LC250 and GigaZ [5].

studied. In order to disentangle whether the materials shows changes due to heat or to radiation stress, also material tests have been performed with a dilatometer, where the unirradiated ILC target have got both fast and cyclic thermal stress in the range of T = 300^0-800^0 C. Different heating/cooling rates of 25^0C/s-100^0C/s with different T_{max} have been used, see Fig. 4 for an example under step-wise heating. The results are listed in [8] and a summarizing paper is in progress [9].

The results of all tests show that the undulator target will stand the expected load.

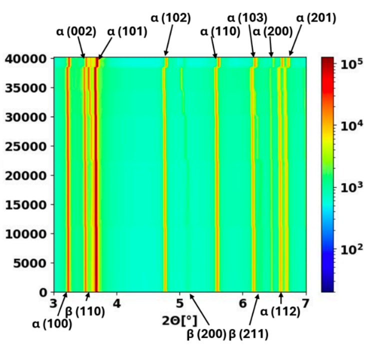

Figure 4. Visualisation of the recorded diffractograms for the step-wise heated Ti-6Al-4V sample [9].

2.3 Rotating Wheel Design Activities

The ILC target wheel of 1m diameter is foreseen to rotate with 2000 rpm, i.e. 100 m/s tangential speed, so that every 7-8 s the load hits the same target position. The photons provide a power of about 60 kW, but only a few percent of the photon energy is deposited in the target, about 2 kW.

The wheel is cooled via radiation only in the vacuum chamber, see Fig. 5 (left panel) [13]. The vacuum tank is embedded in a stationary water cooler. Since the cooling via radiation is sufficient, magnetic bearings are a suitable support element for the rotation, the axis is 'floating' in the magnetic field. Such magnetic bearings are a standard component for such fast rotating devices and are used, for instance, for Fermi choppers or vacuum pumps etc. First technical drawings have been presented, Fig. 5 (right panel) [15]. Technical specifications have been formulated and are still getting fine tuned based on current simulations. Correspondingly, the discussions with the Canadian SKF Company for Magnetic Bearings have been started concerning a full engineering design and prototyping work.

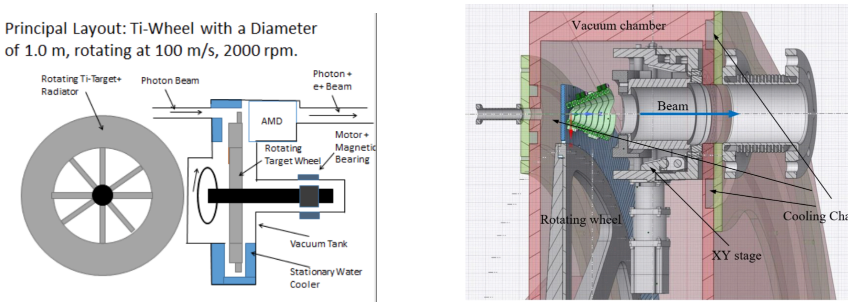

Figure 5. Left panel: Rotating target wheel in vacuum, cooled via radiation only with magnetic bearings as support elements; the vacuum tank is cooled via a stationary water cooler [13]. Right panel: Technical drawings of the support elements and the magnetic bearings [15].

Further simulations and further technical drawings for the complete unit –rotating wheel and a pulsed solenoid as optic matching device– have been performed and presented at this workshop [15], see Fig. 6.

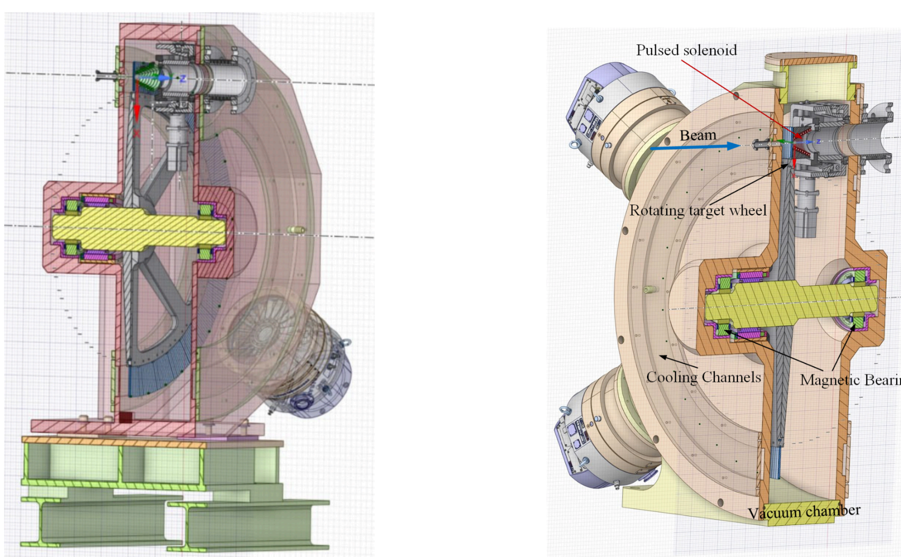

Figure 6. Technical drawings of the whole unit, rotating wheel and pulsed solenoid as optic matching device [15].

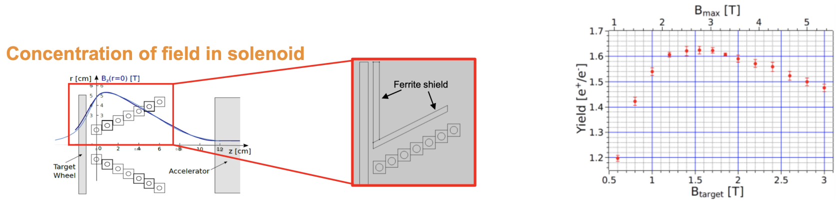

Figure 7. Left panel: Left panel: Ferrite shielding inside the pulsed solenoid, 2D and 3D simulations with COMSOL including the rotating target (100 m/s) and a peak current of 45 kA [12]. Right panel: Expected positron yield depending on the field B_{target} at the target exit and the maximum field B_{max} [13].

2.4 Pulsed Solenoid Prototype Design

Substantial recent progress has been achieved towards manufacturing a (down-scaled) prototype for an ILC pulsed solenoid used as optic matching device. Due to the long 1 ms photon pulse length incident on the target, former designs of a flux concentrator have not been successful and would have led to unstable luminosity conditions that are unacceptable for the physics processes. Therefore, a pulsed solenoid has been proposed [10, 11], whose magnetic field seems to be perfectly well suited for capturing, see Fig.7. Implementing even a shielding system would allow a tuning between either higher positron yield or less beam loss power. In both cases higher yield of the required > 1.5 at the damping ring will be achievable [14].

Within the ITN prototyping of such a pulsed solenoid is envisaged and manufacturing drawings have been done, see Fig.8, for more details see [15]. Currently producing such prototypes via 3D-printing are discussed. First measurements of the fields with 1 kA (pulsed and DC) are planned for these prototypes, extended to 50 kA both in a single pulse mode and finally with a pulse duration of 5ms at 5 Hz, currently it is under discussion at which location these tests can be performed, most probably within the ITN initiative at CERN.

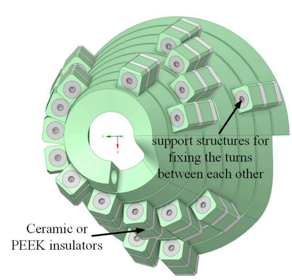

Figure 8. Manufacturing drawings of a prototype for the pulsed solenoid at the ILC $e+$ source [15].

2.5 Plasma Lens Design

Plasma lenses could be an alternative for the pulsed solenoid as optic matching device on a long term timescale, potentially offering even higher positron yields without increasing the target load.

A prototype for a plasma lens has been designed and constructed and its field has been simulated in detail. The experimental tests are still ongoing [16] in the ADVANCE Lab at DESY, where the available peak current is limited to about 350 A. Therefore the prototype has been downscaled by about a factor 4 compared to the full size ILC design. A surprising copper coating inside the plasma lens has been observed, see Fig. 9. The source for such a plasma discharge is still unknown, but further tests under different conditions, for instance using W-Cu electrodes, are ongoing [16].

On the MHD–simulation side the implementation of Ar is under work, and a code with progress towards code generalization is under work.

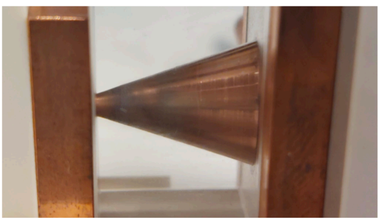

Figure 9. Plasma lens with copper coating [16, 17].

3 The HALHF Design

In order to overcome cost and sustainability problems for high-energy collider new accelerating technologies are mandatory. Plasma acceleration has a great potential, but still its application in high-energy collider physics is very limited. Although progress towards ideas for solving the positron acceleration problem in plasma has been done, a clear path to a feasible solution is not yet obvious [18].

Therefore a Hybrid Asymmetric Linear Higgs Factory (HALHF) Design has been proposed, consisting of a staged electron beam plasma acceleration and a SRF accelerated part for the positron arm [19, 20], see Fig. 10. Due to the very compressed electron section a short e^- tunnel is required. In the current baseline design, a conventionally accelerated e^+ beam of about 30 GeV collides with a beam-driven plasma accelerated e^- beam of 500 GeV, leading to a cms-energy of 250 GeV, $\sqrt{s} = 2\sqrt{E_{e^-} E_{e^+}}$. However, since polarized positrons are substantial for achieving the physics goals [2], the adaption of a polarized-positron scheme for HALHF is under discussion.

There are also discussions to use the HALHF design as an later upgrade stage of the ILC250, i.e. colliding the plasma-accelerated e^- of 500 GeV with the 125 GeV SRF-accelerated e^+. With such an set-up an e^+e^--linear collider with a cms of about 500 GeV could be obtained in the ILC250 tunnel, opening a window to access directly the trilinear

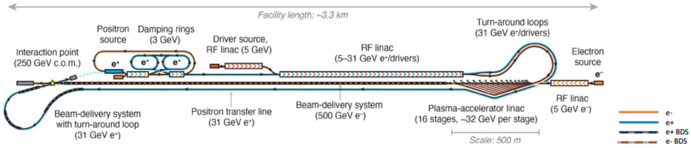

Figure 10. Preliminary set-up of the HALHF baseline design [19, 20].

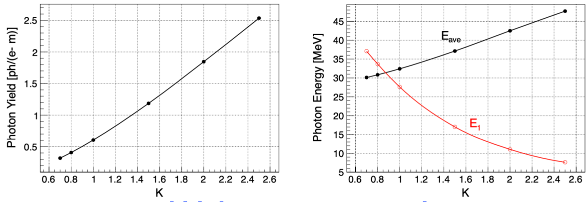

Figure 11. Photon yield (left panel) and the energy of photons (right panel) versus the undulator K-value. E_{ave} is the average photon energy and E_1 is the energy cutoff of the 1st harmonic [22].

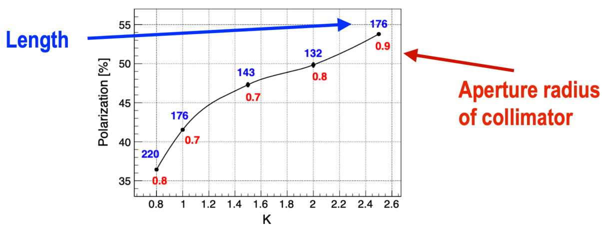

Figure 12. Positron polarization versus K-value without using a collimator but an optic matching device generating 3.2 T peak field on beam axis. The blue numbers indicate the required undulator length [22].

Higgs couplings that are of utmost importance for understanding the Higgs potential and the history of our Universe [21].

3.1 First steps towards an undulator-based positron source for HALHF

Due to the recent progress on the development of the ILC undulator-based e^+ source, it is promising to study whether this scheme can be adapted for HALHF. Since the plasma staging process on the e^- arm is an absolute novelty, the proposal is to use the fully accelerated e^- beam as undulator drive-beam.

The ILC250 undulator-based scheme uses a drive-beam energy of 125 GeV, therefore the undulator parameter have to be adjusted for such higher driver-beam energy.

The starting point for further optimizations, the undulator parameters of the cms=1 TeV ILC-option [22] can be taken, i.e. an undulator with 174 m length, a high magnetic field with $K = 2.5$ and an undulator period of λ =43 mm: the calculation of undulator radiation is based on Kincaid's model [23]. The efficiency of photon generation in such an undulator for different K values is shown in Fig. 11 (left plot). The photon yield has been normalized per electron and meter of undulator. The photon energy cut-off of the 1st harmonic and the average photon energy are shown in Fig. 11 (right plot).

The impact of the undulator field on the e+ polarization is shown in Fig. 12.

With such a parameter set even a high polarization of 54% might be achievable for the positron beam. However, due to the high K value higher harmonics are involved, leading to a higher mean photon power and a higher energy spread, i.e. the e^+ capture might become more difficult. Detailed simulations with the program CAIN adapted for undulators [24] are now under work.

4 Conclusions and Outlook

The undulator-based positron source for the ILC baseline design is a mature design. Undulator simulations including a realistic magnetic field and a masks system have been finalized.

Within the ITN a prototype of the chosen optic matching device for the baseline design, the pulsed solenoid, have been progressed and manufacturing drawings have been finished. First experimental tests with the prototype are ahead. Technical drawings of the rotating wheel have been done and discussions with a manufacturing company concerning the magnetic bearings have been started.

Plasma lens as alternative future optic matching device are in progress as well. First tests have been performed. A measurement of the magnetic field is foreseen.

Furthermore, simulations with the code CAIN for an undulator-based positron scheme for the HALHF design with a cms-enery of 250 GeV have been started in order to adapt this scheme also for polarized positron source for a HALHF collider. As a future vision the HALHF scheme could also be regarded as an possible energy upgrade option of the ILC250, offering e^+e^- collisions at a cms-energy of 500-550 GeV in the ILC250 tunnel [25, 26].

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