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APPLICATION OF PLASMA LENSES AS OPTICAL MATCHING DEVICE FOR POSITRON SOURCES AT LINEAR COLLIDERS

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Abstract

In the baseline design of the International Linear Collider (ILC) an undulator-based positron source is foreseen. The proposed luminosity of the recently chosen first energy stage with $\sqrt{s} = 250\,\mathrm{GeV}$ requires an improvement by a factor of 2500 to the world's first linear collider, the past SLC experiment. This ambitious luminosity goal can only be achieved, if all technological limits are being pushed. One such area is the captured positron number, which is primarily determined in the capture section within the positron source and specifically by its optical matching device. It is responsible for transforming the phase-space of the outgoing particles produced in the target for the succeeding accelerator sections. The plasma lens is a new candidate for this task, providing a specifically adequate method due its magnetic field being azimuthal. Optimizing an idealised tapered active plasma lens for the ILC led us to a design with improved captured positron yield, outperforming ILC's currently proposed quarter wave transformer by approximately 50%. The captured yield also proved to be stable within ±1.2% for deviations in design parameters of ±10%.

OPERATION CYCLE OF AN ACTIVE PLASMA LENS

An active plasma lens (PL) consists of an open cylindrical cavity (capillary) with ring electrodes around both ends and gas inlets. The capillary's symmetry axis coincides with the beam axis.

In the first step, gas (e.g. H_2) is introduced into the capillary. Followed by applying some kV pulsed voltage to the ring electrodes, producing a strong longitudinal electric field inside the capillary. In fact the field is of such magnitude that the neutral gas atoms are ionized and form a ion-electron mixture, the so called plasma. Whereas the ions' momenta are virtually unchanged as a result of their high rest mass, now the electrons are accelerated in longitudinal direction by the electric field, forming a short-lived electric discharge current of some kA. The discharge current in longitudinal direction in turn generates an azimuthal magnetic field. Now inserting a charged particle bunch leads to a radial force, resulting in a focused bunch exiting the plasma lens. Depending on the discharge current's life time, which is limited by the high voltage pulse, multiple bunches or even a whole particle pulse can be transformed. Afterwards the electrons and ions recombine and the gas disperses through the capillary openings into the vacuum. This marks the end of the duty cycle and a new one can be initiated.

ISSUES OF CONVENTIONAL OPTICAL MATCHING DEVICES

The optical matching device (OMD) resides right between the target and the pre-accelerator section and is responsible for matching the phase-space of the produced particles appropriately to the succeeding accelerator sections. This requires the transformation of the initial particles from a highly divergent beam with a small effective cross-section to a wide, parallel one.

In the past this problem has been approached by different types of sophisticated coils like the quarter wave transformer (QWT) and flux concentrator (FC). Both have fundamentally a problem with strong dephasing. Also, the QWT and FC also suffer from chromaticity and eddy currents in rotating targets, respectively. The Plasma lens as a new alternative OMD option could have less issues in those three areas.

Dephasing

The dephasing is concerned with the longitudinal dynamics of the particle bunch within the OMD. The longitudinal size is primarily determined by the effective length of the trajectory where the bunch is forced by the focusing magnetic field. Both the quarter wave transformer and the flux concentrator utilize currents flowing circularly around the beam axis and therefore produce a primarily longitudinal magnetic field, which results in a helical trajectory. However, the plasma lens with its longitudinal discharge current produce an azimuthal magnetic field, leading to a sinusoidal trajectory. In principal a sinus is favourable over a helix due to the shorter effective path the particles traverse, giving the bunch less time to fly apart due to the bunch's wide energy spread pre-acceleration. In Fig. 1 the difference in degree of the dephasing can be observed. Both plots show the longitudinal particle distribution with information on the momentum deviation. The left plot belongs to the plasma lens and the right plot to the quarter wave transformer. The red circles highlight the bunch extensions, showing that the plasma lens provides a compact, focused particle bunch, in comparison to the much wider spread bunch of the quarter wave transformer.

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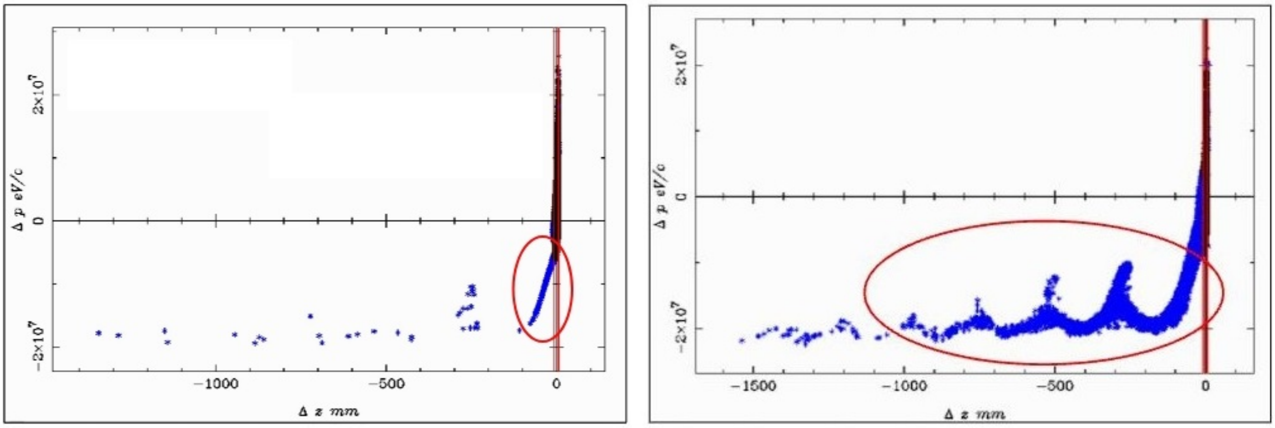

Figure 1: Longitudinal particle distribution after focusing. The red vertical lines mark the 14 mm longitudinal cut. The red circles highlight the degree of dephasing. Left: Plasma lens. Right: Quarter wave transformer.

Chromaticity

The chromaticity is determined by the energy dependence of the focusing process. In general, particles with energies deviating from the design energy will experience an off-design focusing. Or in other words, the focal length is an energy dependent quantity, limiting the effectiveness of the process. The quarter wave transformer's chromaticity is high, while the flux concentrator and the plasma lens offer smaller energy dependence, making both of them broad energy band devices.

Eddy Currents

Due to the OMD's natural proximity to the target, the effects and risks of edge fields spilling into a rotating, conductive target have to be taken into account. Indeed, a magnetic field perpendicular to the target's motion induces an eddy current in the latter, leading to the exertion of a counteractive drag force. The result is stress on the target's propulsion with potential repercussion on its lifespan or immediate malfunction.

As the QWT and FC's magnetic fields are similar to that of a solenoid, their longitudinal fields within the device reach out to form closed loops. This means that edge fields will inevitably penetrate the target. The effects are manageable for the quarter wave transformer but are more problematic for the flux concentrator. The plasma lens avoids this issue completely due to its azimuthal magnetic field lines, which form closed loops inside the device.

OPTIMIZATION OF THE TAPERED ACTIVE PLASMA LENS

In order to explore the plasma lens' capabilities as an OMD, it has been both implemented in the ILC's positron source design and compared with the QWT design, which is currently proposed OMD for the ILC positron source. The simulations have been conducted with ASTRA [1].

Set-up

The input particle distribution stems from CAIN [2] and GEANT4 [3] simulations for the undulator driven positron source with a 7 mm Ti-6Al-4V target, only containing positrons and neglecting all electrons [4].

Solely the first structure of the pre-acceleration section, a standing wave tube (SWT), was taken into account for the optimization process. This approximation has been made to save simulation time and some test simulations have been conducted to successfully ease concerns of resulting inaccuracies. The electric field of this single SWT was implemented in an idealized form by neglecting any kind of losses. In fact, the standing wave is sinusoidal with a constant amplitude of 16.08 MV m^{-1} operating in L-band and π-mode. The geometry was approximated by a 1.27 m long, circular tube with an aperture of $2a = 60$ mm.

Finally we used for the tapered active plasma lens the following approximations: the electric current density inside the capillary was assumed to be radially homogeneous at every longitudinal position and overall constant in time. Furthermore all plasma lens designs, which were simulated during the optimization process, share on the one hand their starting point at 1 mm distance to the target and on the other hand the electric current strength of $I_0 = 3$ kA. All remaining parameters were open for optimization, i.e. the plasma lens length, opening radius, tapering order, tapering strength, plasma lens-standing wave tube distance and the standing wave tube phase.

Results

The optimization process at an electric current of 3 kA concluded with a tapered plasma lens parameter set (see Table 1) leading to a 25.9% positron capture efficiency within the damping ring's energy acceptance of 0.75%, which is equivalent to a 14 mm longitudinal cut of the positron distribution. This result is very similar to the current simulation results for the ILC's currently proposed QWT design with ~ 26% [5] capture efficiency. Increasing the plasma

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lens' electric current to 6 kA and 9 kA yields a capture efficiency of 34.9% and 40.6%, respectively. The latter being an improvement of roughly 50% over the QWT. It has to be emphasised, that the optimization process has been conducted only for the base electric current of 3 kA and not for the subsequent higher currents. Nevertheless, test simulations suggest the optimal plasma lens design to be largely independent of the electric current.

Table 1: Optimized Plasma Lens Parameter Values at Electric Current $I_0 = 3\,\mathrm{kA}$

Parameter name	Symbol	Optimal Value
Plasma Lens Length	z_{max}	5.9 cm
Opening Radius	R_0	3.8 mm
Tapering Order	n	1
Tapering Strength	g	$300\,\mathrm{m}^{-1}$
PL-SWT distance	d	1 cm
SWT Phase	φ_0	230 deg

Furthermore the optimized plasma lens design at $I_0 = 3\,\mathrm{kA}$ has also been tested for its stability in capture efficiency by deviating all PL parameters independently by ±10%. This resulted in capture efficiency deviations within ±1.2% (see Table 2). Similar deviations are to be expected for the optimized designs at 6 and 9 kA.

Table 2: Deviations in positron capture efficiency for Deviations in Optimized PL Parameter Values at $I_0 = 3\,\mathrm{kA}$

Parameter name	-10% offset	+10% offset
PL length	−0.12%	−0.28%
Opening radius	−0.43%	−0.21%
Tapering strength	−0.08%	−0.13%
Current strength	−1.13%	+1.03%
PL-SWT distance	+0.05%	−0.07%
SWT phase	−0.49%	−0.32%

An additional observation can be made from this test, namely that the capture efficiency can be further improved by decreasing the distance between plasma lens and accelerator structure.

CONCLUSION

Optimizing an idealised plasma lens model to find a possible alternative for the ILC's optical matching device has been fruitful. Simulations of the proposed design show a significant improvement in positron capture efficiency of up to approximate 50% over the quarter wave transformer, foreseen in the current baseline ILC design. Furthermore the captured positron yield also proved to be stable within ±1.2% for independent parameter deviations of ±10%. In the future, further investigations towards a tapered active plasma lens as optical matching device are foreseen by additional simulations as well as by real prototyping to test the actual effectiveness and to explore further technical details.

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