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PREPARATION OF A PROTOTYPE PLASMA LENS AS AN OPTICAL MATCHING DEVICE FOR THE ILC e^+ SOURCE

M. Formela*, N. Hamann†, G. Moortgat-Pick[1], II. Institute of Theoretical Physics, University of Hamburg, Hamburg, Germany
K. Flöttmann, G. Loisch, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[1]also at Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

In recent years, high-gradient, symmetric focusing with active plasma lenses has regained significant interest due to the potential advantages in compactness and beam dynamics compared to conventional focusing elements. One potential application is the optical matching of highly divergent positrons from the undulator-based ILC positron source into the downstream accelerating structures. A collaboration between University Hamburg and DESY Hamburg has been established to develop a prototype design for this application. Here, we discuss beam dynamics simulation results, preliminary parameters of the lens prototype, and the current status of the prototype design.

INTRODUCTION

At the International Linear Collider (ILC) electron and positron beams will be collided at up to 500 GeV centre-of-mass energies to enable, e.g., precision measurements of Higgs boson properties. The positron source is planned to be based on pair production of electrons and positrons by the interaction of high energy photons with a Titanium-target wheel rotating at high speed. Due to the large divergence of the produced positrons, an optical matching device (OMD) has to be placed as close as possible to the rotating target, to capture the largest possible amount of positrons. A high capture efficiency, also called yield, is essential to fulfill the luminosity requirements of the ILC physics programme.
Currently, the baseline option for this OMD is a quarter-wave transformer magnet. Despite a higher possible yield, flux concentrators cannot be applied at the ILC positron source due to the variation of their focusing field over the ILC's 1 ms long bunch trains. To increase the yield, it was proposed to use an active plasma lens (APL) as an OMD instead.

In an APL, a gas column is ionised to a plasma and a high-amplitude current pulse is directed through this plasma. A beam that travels co-axially through this plasma column experiences a radial force from the azimuthal magnetic fields induced by the lens' current. Compared to conventional focusing devices, this scheme features several advantages:

- fully symmetric focusing in both transverse planes
- high focusing gradients due to the close proximity of plasma current and beam
- focusing transverse to main direction of motion
- space charge mitigation by plasma electron motion
- reduced heat load on target due to minimal field outside of lens.

Nevertheless, the application as an OMD at the ILC positron source also poses several challenges on the plasma lens, which have not yet been tackled in APL research:

- MHz burst operation of plasma lens compared to the state-of-the-art few Hz operation
- high gas load on the downstream, close-by accelerating cavities.

A project has been initiated at the University Hamburg in collaboration with DESY Hamburg to explore the capabilities and limits of active plasma lenses for this application.

PARTICLE TRACKING SIMULATIONS

To explore the achievable positron yield and the operational parameters of the APL, particle tracking simulations have been performed using ASTRA [1]. A wide range of lens designs have been simulated, varying the total electric current I_0, the opening radius R_0, the exit radius R_1, the APL length L and the taper order n.

Figure 1 summarizes the results by showing the optimal achievable positron capture efficiency – the number of captured positrons relative to the total number – for every examined combination of electric current and taper order. It can be seen that a linear tapering ($n = 2$) is superior to weaker and stronger tapering in nearly every case, except for currents of 2 kA and below.

Results

A plasma lens design has been chosen to be the reference point for future prototype developments. Parameters for said design can be seen in Table 1. The simulated capture efficiency for this design lies at about **43 %** with 42917 total simulated positrons. Even though higher efficiencies can in simulation be achieved by assuming higher currents, the chosen set of parameters is considered a reasonable compromise between capture efficiency and technical feasibility.

The capture efficiency of this design proved to be stable in simulations for variances in the design parameters as can be seen in Table 2. In all cases single parameter errors of ±10 % lead to efficiency loss below −5.0 %.

* manuel.formela@desy.de
† niclas.hamann@desy.de

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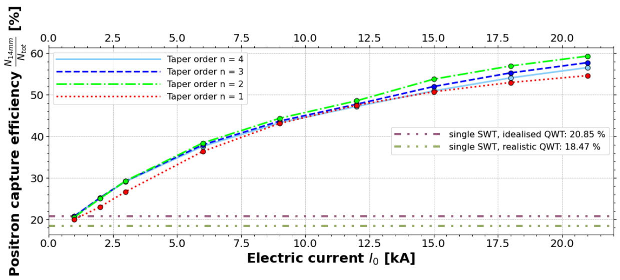

Figure 1: Impact of the total current I_0 on the positron capture efficiency. Each curve is dedicated to a taper order. Each data point represents the most efficient plasma lens design for the respective electric current I_0 and taper order n.

Table 1: Optimized Plasma Lens Parameter Values at Electric Current $I_0 = 9\,\text{kA}$

Parameter name	Symbol	Optimal Value
Plasma Lens Length	z_{max}	60 mm
Opening Radius	R_0	4.3 mm
Tapering Order	n	2
Tapering Strength	g	0.082 mm^{-1}
PL-SWT distance	d	10 mm
SWT Phase	φ_0	225 deg

PROTOTYPE DEVELOPMENT

Building a prototype comes with a few challenges. It would be expensive and a significant effort to build a pulsing circuit powerful enough to achieve 9 kA. Therefore, the design parameters of the prototype setup are rescaled to the current amplitude that is available with MHz repetition rates at DESY at the moment. With this existing equipment, the peak current amplitude lies at about 350 A. This means that the radius has to be downscaled with a factor of $a = \sqrt{9000\text{A}/350\text{A}} \approx 5.07$ due to the current density being $J = I/2\pi R^2$. With this downscaled radius, the current density is the same as in the actual size plasma lens. If the length should also be downscaled by this factor a, the tapering strength g has to be upscaled by a due to the aperture radius along the z-axis being $R(z) = R_0 * (1+gz)^{n/2}$. Figure 2 shows how the dimensions of a downscaled plasma lens would look like.

DIAGNOSTICS DEVELOPMENT

To judge on current density homogeneity or the effects of beam-plasma interaction it will be necessary to characterise the plasma properties achieved in the prototype setup. The necessary diagnostics methods for this have to be set up and optimised. For this purpose, a plasma cell was set up at DESY which will serve as a test bed of diagnostics methods. The plasma cell was previously used for plasma wakefield acceleration at PITZ in Zeuthen, Germany [2]. Now out of service, the PITZ cell was re-commissioned at DESY in Hamburg, Germany. The properties of the PITZ cell can be seen in Table 3.

Table 2: Stability of the capture efficiency for the picked plasma lens design. All design parameters (except for the taper order n) have been varied by ±10 % from the design value. Both setups, single SWT and extended SWT, have been examined.

		Single SWT		Extended SWT	
Parameter name	**Symbol**	**−10% offset**	**+10% offset**	**−10% offset**	**+10% offset**
Electric current	I_0	−4.1	+3.0	−4.7	+3.8
Initial radius	R_0	−0.6	−0.6	−0.2	−0.7
Exiting radius	R_1	−0.4	−1.6	+1.1	−2.4
Plasma lens length	L	−1.9	−0.7	−4.5	+1.8
Starting phase	φ_0	−1.0	−1.4	−2.2	−2.9
Target-PL distance		0.0	−1.7	0.0	−0.1
PL-Acc distance		+0.3	−0.4	+0.2	−0.3

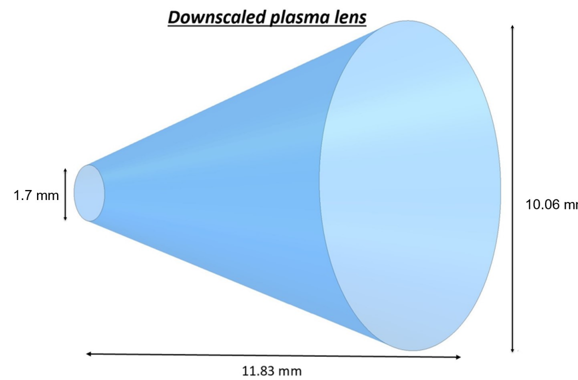

Figure 2: Sketch of the preliminary, downscaled plasma lens prototype for max. current amplitudes of 350 A.

Table 3: PITZ Cell Parameters

Parameter name	Unit	Value
Cell Length	mm	100 – 200
Cell Diameter	mm	10
Gas pressure	mbar	0.1 – 3
Peak current	A	100 – 1000

Measurements of the current pulse timing jitter were performed and the results can be seen in figure 3. Similar measurements will be essential for determining the focusing jitter in the ILC plasma lens prototype.

CFD SIMULATIONS

An important part in designing a plasma lens is the overall structure and how it fits within the general gas injection scheme. Therefore the positioning and shape of the inlet tubes have to be further analyzed. It is essential to know how the gas flow in the capillary takes place. This can be done with 'ANSYS FLUENT'.

The main goals of these simulations, are to design the positions and shapes of the inlets that the gas distribution in the capillary is as homogeneous as possible and to see how the gas flow out of the capillary is going to happen. This is necessary to know because of the standing wave tube near

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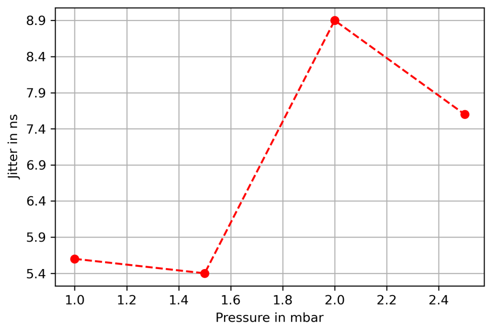

Figure 3: Discharge current rising edge timing jitter at 50 % of max. current amplitude in ns. The cell was filled with Argon gas.

the end of the plasma lens. Because this should be possible without any windows at both ends of the capillary the whole set-up will be inside a vacuum chamber. This means that the standing wave tube must be as gas free as possible to grant full functionality or otherwise it could be destroyed. To see how this gas outflow looks like a vacuum box will be integrated at the end of the plasma lens towards the standing wave tube. To analyze simulation data, different plot methods are considered for further investigation. These plot methods are: density and pressure profiles in both transversal axis of the beamline and pathline tracking of gas particles to understand gas flow within the capillary. All these simulations will be done with Argon. Figure 4 shows a density profile in the yz-plane inside of the capillary.

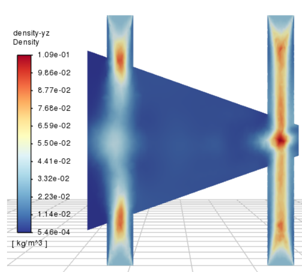

Figure 4: Density profile in the yz-plane inside a downscaled plasma lens.

In Fig. 5 the simulated particle paths in the down-scaled plasma lens prototype are shown, where the particles enter through the four vertical gas inlets and exit through the small and large ends of the funnel-shaped, tapered lens.

Simulations in ANSYS Fluent are in an early stage and will be refined in future work to define the exact setup of the prototype lens and its periphery.

SUMMARY AND OUTLOOK

A project has been initiated at the University of Hamburg in collaboration with DESY Hamburg to explore the suitability of an active plasma lens as an optical matching device for the ILC undulator-based positron source. Particle tracking

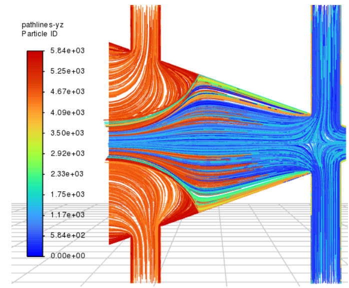

Figure 5: Pathlines of yz-plane inside a downscaled plasma lens.

simulations have been performed to identify a preliminary set of parameters of a plasma lens allowing a large positron yield.

To reduce the requirements on the high voltage drive electronics, a scaled-down prototype will be built and tested in the ADVANCE discharge plasma development laboratory at DESY [3]. Gas flow simulations are ongoing to determine a suitable geometry of the electrodes and the surrounding vacuum vessel of the prototype. In parallel, further parameter optimisation and magnetohydrodynamics simulations of the plasma will be performed.

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