ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA132

STATUS OF HYDRODYNAMIC SIMULATIONS OF A TAPERED PLASMA LENS FOR OPTICAL MATCHING AT THE ILC e+ SOURCE

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Abstract

The International Linear Collider is a proposed electron-positron linear collider, where the positron beam is generated by undulator radiation hitting a target. The resulting, highly divergent positron beam requires immediate optical matching to improve the luminosity and ensure the success of the intended collision experiments. Here, optical matching refers to the process of capturing particles and making them available for downstream beamline elements like accelerators. In the past, this has been done with sophisticated coils, but more recently the usage of a current-carrying plasma, a so-called plasma lens, has been proposed as an alternative. For the International Linear Collider, idealised particle tracking simulations have already been done in the past with the purpose of finding the optimal plasma lens design with respect to the captured positron yield. The proposed design is conical in shape to accommodate for the large beam divergence [1]. Now further research and development of this design is required, including both experiments with a downscaled prototype set-up as well as corresponding simulations modelling the hydrodynamics of the current-carrying plasma. The accuracy of the latter will benefit greatly from the former. In this work, first preliminary hydrodynamic simulations instil confidence into further endeavours.

INTRODUCTION

The plasma lens is a device for the focusing of charged particles via a current-carrying plasma. A plasma lens is called active plasma lens (APL), if the focusing effects are driven externally by, for example, a laser or power supply. In general, an APL consists of a capillary oriented along the beam axis and lateral gas inlets. For an APL driven by a power supply, electrodes are added to both openings of the capillary.

The operation of such an APL starts with filling the empty capillary with a gas (e.g. H_2 or Ar) via the inlets. Afterwards, a high voltage is applied between both electrodes resulting in an electric field inside the capillary. If sufficiently strong, the electric field ionises some of the molecules near the electrode edges creating free electrons in the process. These few free electrons are then accelerated by the same electric field to energies sufficient enough to free additional electrons via impact ionisation. This new generation of free electrons is then also accelerated and causes further ionisation. The same applies to every subsequent electron generation as well. This chain reaction culminates in a partially- or fully-ionised plasma. During this process, the mostly longitudinal electric current increases significantly and induces an azimuthal magnetic field. This azimuthal component leads to the axial symmetric deflection of an incoming charged particle beam. It either focuses or defocuses the beam, depending on the relative orientation between the field, the particle motion and the sign of the charge. While the above gives a basic description of the APL's functionality, more advanced processes, like plasma pinching, have been omitted here.

Possible APL applications include final focusing and particle matching. In theory, an APL should have an advantage over conventional optical matching devices, especially due to the axial symmetric focusing properties from its azimuthal magnetic field.

However, there are three major problems to be solved for the ILC. First, the plasma lens must consistently match successive positron pulses. In the case of the ILC, the positron beam's temporal structure (see Table 1) requires a demanding temporal structure of the discharge pulse. This is problematic, because a combination of discharge pulse duration and repetition rate has to be found, which keeps the disturbance of the plasma low and allows for consistent focusing. At the same time, the combination has to be technically feasible by a power supply.

The second major potential obstacle is the gas outflow from the windowless APL capillary into the downstream accelerator. This vacuum contamination could promote discharges of the accelerator and prevent proper acceleration.

Table 1: Positron Beam Structure with 1312 Bunches per Pulse

	Repetition rate	Duration	Spacing
Bunch train	5 Hz	727 μs	199 ms
Bunch	1.8 MHz	538 ps	554 ns

And lastly, it has to be examined, how the APL components withstand the collective heat load from electric heating and particle beam deposition. A significant heat load could deform the plasma lens set-up. But also a smaller heat load has the potential to lead to contamination of the discharged gas with evaporation from surrounding parts and could lead

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therefore to less optimal discharge behaviour.
In the following, previous progress [1] is briefly summarised to lay the conditions for the subsequent discussion on the hydrodynamic simulations.

Particle Tracking

In a previous working step towards an APL for the ILC e+ source, the APL design parameters have been optimised with respect to the number of matched positrons. For this, particle tracking simulations have been conducted without simulating plasma dynamics, but instead an idealised plasma lens was assumed. The electric current density of an idealised APL is assumed to be purely longitudinal and radially homogeneous

$$\vec{j}(x, y, z) = \vec{j}_z(z).$$

According to the Maxwell equations, the induced magnetic field is therefore

$$B(\rho, \varphi, z) = B_\varphi(\rho, z) = \frac{\mu_0 I}{2\pi R(z)^2}\rho, \quad \text{for } 0 \leq \rho \leq R(z)$$

with the vacuum permeability μ_0, electric current I and capillary radius R.
The parameter optimisation has been performed using the particle tracking code ASTRA [2]. It resulted in an optimal APL design, which is characterised by its conical shape as can be seen in Fig. 1. This design is capable of a positron capture efficiency of about 43 % [1], which is roughly double the amount of the currently proposed ILC optical matching device, the quarter wave transformer [3].
In a next step, the design was also successfully tested for stability of its capture efficiency by introducing single parameter errors of ±10 % into the design. These parameter errors, in any case, led to a relative decline in number of captured particles by at most 5.0 % [1]. For our purposes, this is expected to be stable enough.
Despite these optimistic results, this design is only preliminary and will be altered and further optimised with every new finding in the future. This is especially true, considering these results are based on the ideal APL model, which is only a rough approximation. This makes= hydrodynamic simulations necessary to obtain more accurate magnetic fields, which then can be tested in further particle tracking simulations.

Downscaled Prototype

At this stage of development, it would be important to build the proposed APL design and measure its capabilities in experiments. This is currently not feasible, due to the technically demanding requirements on the power supply and APL's large size making it not suitable for the on-site measuring set-up. To make valuable experiments possible regardless, the design geometry was downscaled by a factor of approximately 5. At the same time, to ensure similar physical effects as in the full scale design, the electric current density was kept constant by adjusting the total current accordingly. The resulting prototype design parameters are found in Table 2. More details on the downscaled prototype and planned future experiments can be found in Ref. [4].

Table 2: Parameters of the Prototype Plasma Lens Design

Parameter name	**Symbol**	**Value**	**Unit**
Electric Current	I_0	350	A
Tapering Type		linear	
Opening Radius	R_0	0.85	mm
Exit Radius	R_1	5.0	mm
Tapering Length	L	12	mm

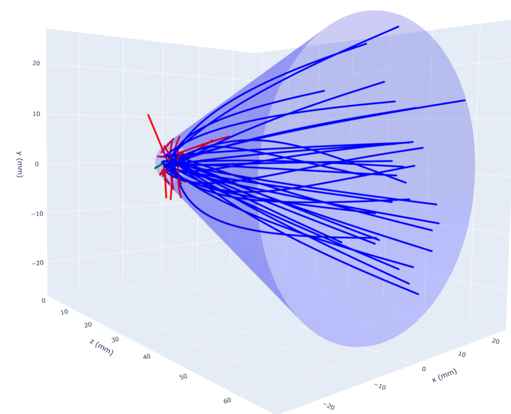

Figure 1: Visualisation of particle tracking in a cone-shaped plasma lens.

HYDRODYNAMIC SIMULATIONS

For the future, full-fledged hydrodynamic (HD) simulations of both the downscaled and full scale APL design are planned to be performed using the finite element software COMSOL Multiphysics® [5]. At this point of time, the downscaled prototype has been simulated by considering only the hydrodynamics (HD) and neglecting any magnetic effects. A brief description of the model and the subsequent results are presented in the following.

Model

These simulations are based on the custom COMSOL Multiphysics® model of Ref. [6], where the plasma is treated as a quasi-neutral, two temperature, reacting fluid. This is because the fast moving electrons shield the electric charge of the ions. Also, the temperature is considered separately for the light electrons and the heavier particles (ions, neutrals). And finally, the plasma composition is calculated using diffusion and reaction rates, instead of calculating it from an assumption of thermal equilibrium.
The discharged gas is hydrogen and the the discharge current is a sine-like half-wave with an amplitude of 350 A and a duration of 200 ns.
The prototype geometry was modelled in 2D, but effectively simulated in 3D by assuming axial symmetry. Except for the

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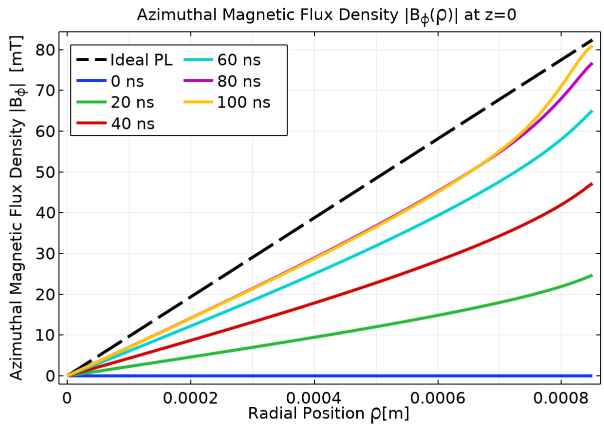
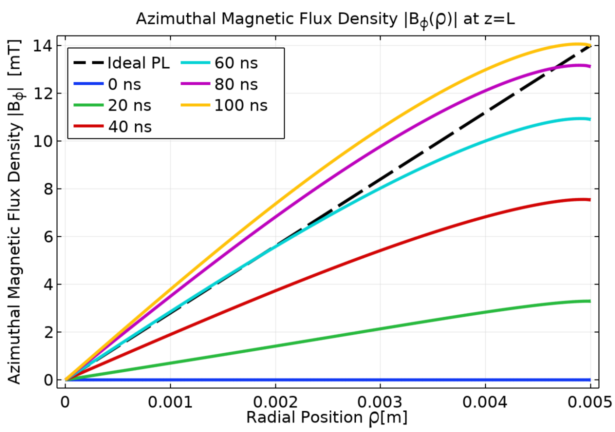


(a) At APL entrance



(b) At APL exit

Figure 2: Radial distribution of the azimuthal magnetic flux density. Solid: HD simulation at various times; Dashed: Ideal model with homogeneous current density.

cone-shaped capillary, the rest of the geometry was simplified. For instance, the electrodes were made to span across the entire capillary openings and no inlets were modelled. Instead, it was assumed that the plasma distribution was homogeneous, but not constant, for all times. And finally, the capillary walls are implemented as perfectly insulating.

Results

Fig. 2 depicts the azimuthal magnetic flux density $|B_\varphi(\rho)|$ plotted against the radial position ρ at the entrance and exit of the APL, respectively. The coloured, solid lines correspond to the HD simulation results at different times, while the dashed, black line belongs to the ideal plasma lens.

According to Fig. 2a, the magnetic field at the entrance is at most approximately 20 % lower for the HD simulation compared to the ideal APL. In contrast, Fig. 2b shows that the situation is reversed at the APL exit. Since the magnetic field at the entrance is more crucial for the capturing process, it is suspected that particle tracking simulations of the field from the HD simulation would result in fewer captured positrons. These are preliminary results meant to give a rough estimate for the deviation from the ideal model.

OUTLOOK

Preliminary hydrodynamic simulations in a simplified set-up show the expected amplitude and radial profile of the magnetic field, although a significant deviation of 20 % can be observed compared to the idealised plasma lens. This is not expected to be a problem, because the proposed APL design was chosen with a massive overhead in the number of matched positrons. Namely, it falls just short of doubling the number of matched positrons compared to the currently proposed ILC device as was shown in past simplified particle tracking simulations [1]. But of course further investigations in form of both, simulations and experiments, have to be conducted before drawing any further conclusions.

One primary area of future investigations is the plasma's response to multiple successive plasma discharge pulses. Especially interesting is the way the APL's focusing properties are affected by the demanding requirements on the pulse repetition rate and duration imposed by the positron beam temporal structure (see Table 1). The goal is to find a discharge pulse structure, which enables consistently effective positron collimation, while still being achievable by a power supply. Another important study to be conducted will be measuring the gas flow from the windowless APL capillary into the downstream accelerator, which could render proper acceleration impossible. And one more potential problem to be examined is the collective heat load onto the APL components stemming from electric heating and particle beam deposition. The heat load could lead to evaporation of the surrounding APL parts, which degrades the gas composition and therefore the discharge behaviour. This would also lead to a shortened lifespan of the device.

Looking forward, for all these studies to provide realistic results, multiple improvements to the existing simulation model are required. This includes, but is not limited to the implementation of Argon instead of hydrogen, more realistic electrodes and discharge pulses and adding inlets.

Finally, the simulated magnetic flux density will be used in particle tracking simulations to optimise the plasma lens shape with respect to the number of captured positrons. At the same time, experiments and measurements will be conducted on the downscaled prototype [4] in the ADVANCE Laboratory [7] at DESY. This will allow for validation of any future simulation results and will be crucial for the success of the plasma lens.

ACKNOWLEDGEMENTS

This project received funding from the German Federal Ministry of Education and Research [Grant No. 05P21GURB1].

Also, we express our deeply felt gratitude towards K. Flöttmann and M. Fukuda for multiple instances of valuable collaboration.

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ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA132

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