Investigation Of Plasma Stability Of The Prototype Plasma Lens For Positron Matching

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Abstract. The quest for novel technologies in the ever-evolving landscape of scientific exploration has led to the investigation of plasma lensing as a potential solution for optical matching devices for all kinds of positron sources. This research becomes increasingly significant as the need for higher event rate demands innovative concepts to increase positron yield and therefore luminosity. A prototype plasma lens has been developed and tested for the first time. Instabilities were observed during the first test trials. This paper presents the results of high-temporal resolution imaging to analyze the discharge instabilities. Furthermore, the results show splitting and bending discharge instabilities and heavy copper coating. Overcoming these challenges is pivotal for a future application of plasma lenses as an integral part of high-performance positron sources.

1 Introduction

The International Linear Collider (ILC) and the hybrid, asymmetric, linear Higgs factory (HALHF) [1] are two of several proposed accelerators being discussed to be part of the next generation of high-performing particle colliders. Both, ILC and HALHF, will allow for high-precision measurements of Higgs boson properties by using polarized electron-positron collisions. Therefore, the overall design of the positron source is being discussed thoroughly. One possibility is to direct undulator radiation onto a rotating titanium target wheel to generate electron-positron pairs. Due to the large divergence of the produced positrons, an optical matching device (OMD) will be required to capture the largest amount of positrons as possible and to strongly decrease the divergence for downstream accelerator structures. Therefore, the OMD has to be placed as close as possible to the target. Currently, a quarter wave transformer or a pulsed solenoid are the preferred proposals for the OMD. Because of the variation in the focusing field over the ILC's 1 ms long bunch trains, flux concentrators are not suitable for use at the ILC positron source, even though they have the potential to produce a higher positron yield.

More recently the usage of current-carrying plasma has been proposed as an alternative, the active plasma lens (APL). In an APL, a plasma is created by ionizing a gas column, and a high-amplitude current pulse is directed through the plasma, inducing azimuthal magnetic

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fields that produce a radial force on a beam that travels through the column. Although an APL promises some great advantages, several challenges have to be addressed [2]. The University of Hamburg, in collaboration with DESY Hamburg, has launched a project to investigate these possibilities and constraints of using active plasma lenses for this purpose. Idealized particle tracking simulations have already been done with the purpose of finding the optimal plasma lens design with respect to the captured positron yield. Now further research and development of this design is required, including both experiments with a prototype set-up as well as corresponding simulations modeling the hydrodynamics of the current-carrying plasma and the resulting magnetic field. In the following an insight into the test set-up and the resulting outcomes will be given.

2 Prototype Development

In [2], it was described how particle tracking simulations were used to determine a theoretical design. The program used for these simulations is ASTRA [3] by K. Flöttmann. Based on this simulated design, shown in [4], the prototype design has been down-scaled by a factor of 5.07. This had to be done because the ADVANCE Lab at DESY [5], where the prototype is in operation, limits the available peak current to 350 A. The prototype design was chosen according to the results of gas flow simulations being performed on different gas inlet designs shown in [4]. The overall principle is to press low-oxygen copper electrodes against both openings of the plasma lens. In order to ensure that noticeable gas leakages will only occur at the designated openings of the lens, o-rings were used to seal the contact surfaces between electrodes and plasma lens and between electrodes and holders. The plasma lens is made out of one 20 mm x 20 mm x 12 mm sapphire block. There are three different holders all made out of Polyetheretherketon (PEEK): two for both sides of the plasma lens with the holder at the larger diameter of the lens also including the gas inlets and the third holder is used to fixate the position of the plasma lens properly. The previous gas flow simulations showed that angled gas inlets were preferred. In order to enable the drilling of the angled gas inlets, the edges of the holder had to be bevelled. After the assembly the prototype can be mounted onto the adjustable hexapod inside the vacuum chamber. In Fig. 1 an image of the finished prototype set-up in operation is shown. The parameters of the plasma lens design are shown in Table 1. All components were made in the workshop at DESY.

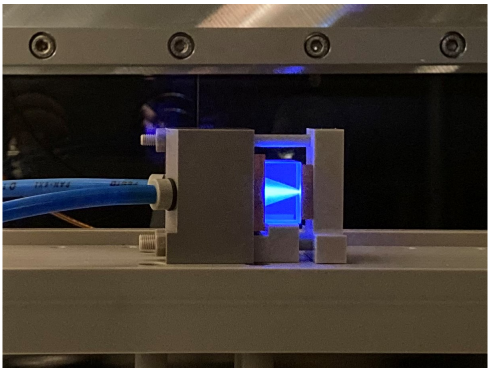

Figure 1. Plasma discharge of prototype plasma lens inside vacuum chamber at ADVANCE Lab.

Table 1. Parameters of the Prototype Plasma Lens Design

Parameter name	Symbol	Unit	Value
Peak Electric Current	I_0	A	350
Tapering Type			linear
Opening Diameter	R_0	mm	1.7
Exit Diameter	R_1	mm	10
Tapering Length	L	mm	12

3 High-Temporal Resolution Measurements

The first operation test in the ADVANCE Lab were successful and plasma was created. However, it was observed that the gas discharge showed an unstable behavior under certain circumstances. This is not completely unexpected as this type of plasma lens is quite unconventional compared to the usually used lenses. Therefore, an ICCD camera for high-temporal resolution imaging of the emitted plasma light was used. The goal was to identify specific unstable modes, to analyze them and determine their origin. First measurements of this kind were performed in December 2023. Here, one could identify two different kinds of unstable modes. In the first one, the discharge is shortly being bent upwards. Extreme cases also showed the discharge almost being folded into a loop. This could possibly indicate a kink instability in the plasma, but more measurements are needed for confirmation. In the second observed instability mode, one can see a splitting of the discharge into two or more discharge channels as shown in Fig. 2. In almost all the cases the splitting results in only two discharge channels. So far there is no clear explanation why this is happening. In an ideal conical plasma lens the plasma should be distributed uniformly inside the cone. As one can see in Fig. 2, this is not the case. Here, the plasma is mainly limited to the beam axis.

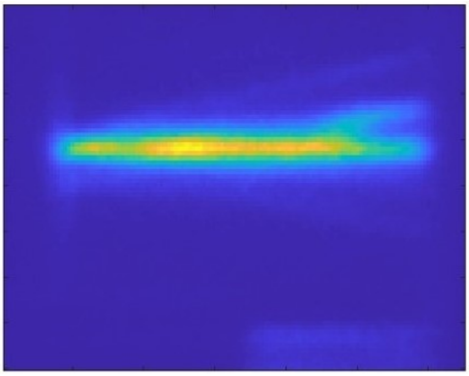

Figure 2. Observed instability where the discharge channel is being split. This picture was taken on December 23 before any copper coating came up.

Based on these first observations, new measurements were performed between February and March. The heart of these measurements consisted of plasma development measurements from 0 µs to 1.5 µs with an exposure time of 50 ns at different flow rates. Additional measurements consisted of: using pre-ionized plasma by applying a glow discharge, long-time plasma evolution up to 4 µs and plasma stability by changing the electrical current direction. The last one is particularly important as the plasma lens could not only be used for positrons but also for electrons, depending on the direction of the electrical current. For all measurements, different flow rates from 0.2 mbar· l/s to 1.5 mbar· l/s of argon only were used. After approximately 24,000 shots within 8 days the lens was taken out and one could see a strong copper coating inside the conical lens which can be seen in Fig. 3. This was unexpected as under these operation conditions no other cell tested at the ADVANCED Lab had shown a similar thickness of copper coating. One should note, however, that the design of this plasma lens strongly differs from all other designs tested before.

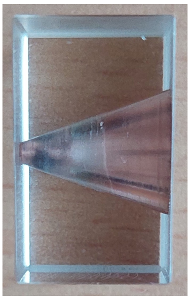

Figure 3. Visible copper coating inside the plasma lens after 8 days of operation.

After evaluating the collected data it was obvious that the copper coating strongly affected the analysis process. Because of the coating a lot of light was not detected by the camera. The light was particularly blocked at the entry and the exit of the plasma lens. Therefore, the previously observed instabilities could no longer be identified by the analysis. It is also most likely that the copper coating inside the lens is changing the current and therefore also the plasma distribution. Considering this outcome, plots and graphics were made to qualitatively describe the behavior of the copper coating and the visualization of the blocked emitted plasma light. Figure 4, for instance, shows how the overall plasma distribution along the beam axis looks like for different time steps. Each column represents an average of 100 shots recorded for a different time step. This measurement was taken after roughly 23,000 shots and 8 days of testing. Although the peak light intensity is high compared to earlier measurements, one can clearly see the copper coating. At all time steps, absolutely no plasma light was detected within the first 4 mm of the plasma lens. It gets even more obvious if one compares Figs. 4 and 5. Here, one can see the same plot for two different measurements taken roughly 22,000 shots apart from each other. Although the peak intensity is lower one can clearly see that plasma light is being detected inside the first 4 mm in Fig. 5.

4 Summary and Outlook

The project has been initiated at the University of Hamburg in collaboration with DESY Hamburg in order to explore the suitability of an active plasma lens as an optical matching device for undulator-based positron sources at high-energy linear colliders. First operation tests have been performed in the ADVANCED discharge plasma development laboratory at DESY [5]. The results showed unstable discharge modes under certain conditions and heavy copper coating due to high electrode erosion. The next step is the fabrication of new copper and tungsten-copper electrodes in order to investigate the electrode erosion in more detail. The goal is to understand the origin of the copper coating and reduce that effect. In parallel, further parameter optimisation and magnetohydrodynamic simulations of the plasma will be performed.

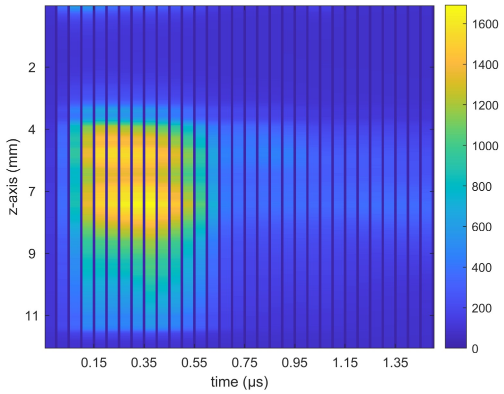

Figure 4. Plasma light along the beam axis for each time step up to 1.5 μs. This measurement was taken after roughly 23,000 shots.

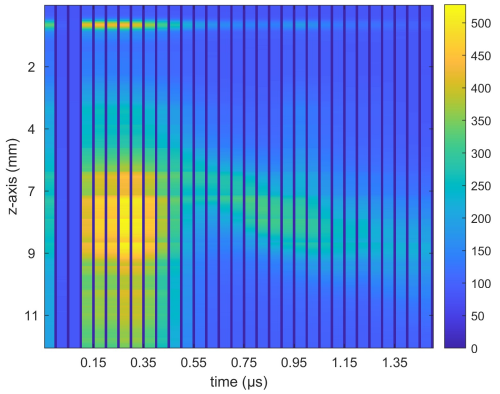

Figure 5. Plasma light along the beam axis for each time step up to 1.5 μs. This measurement was taken after roughly 1,000 shots.

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