UPGRADES OF THE EXPERIMENTAL SETUP FOR ELECTRON BEAM SELF-MODULATION STUDIES AT PITZ

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Abstract

The self-modulation instability is fundamental for the plasma wakefield acceleration experiment of the AWAKE collaboration at CERN where this effect is supposed to be used to generate proton bunches short enough for producing high acceleration fields. For ease of experimentation it was decided to set up a supporting experiment at the electron accelerator PITZ (Photo Injector Test facility at DESY, Zeuthen site), given that the underlying physics is the same. The goals are to demonstrate and investigate in detail the self-modulation of long electron beams.

In 2015 a first set of experiments was conducted utilizing as key elements a novel cross-shaped lithium plasma cell and an ArF excimer laser for plasma generation. No self-modulation was observed yet because of various experimental shortcomings. The properties of the experimental setup were studied in detail and in this contribution we report about the upgrades which are projected to enable the observation of the self-modulation in the upcoming experimental run.

INTRODUCTION

Plasma wakefield acceleration has the potential to revolutionize the acceleration of charged particles to relativistic velocities. The reason for this is that achievable acceleration gradients are orders of magnitude higher compared to conventional technologies based on RF fields. In the basic setup a driver propagates through a plasma, creating wakefields, which accelerate a following witness bunch. Typically this driver is an electron bunch or a high intensity laser pulse, but in the experiment of the AWAKE collaboration, which is under preparation at CERN [1, 2], a proton bunch will be utilized as the driver. The reason for this is that proton bunches can be accelerated to very high energies, enabling single stage plasma acceleration of electron witness bunches to TeV energies [1]. Available proton bunches are orders of magnitude too long for efficient acceleration, but this can be adjusted by separating the long bunches into driver bunchlets with appropriate length by utilizing the self-modulation instability [3].

To study this effect in detail a supporting experiment was set up at the electron accelerator PITZ (Photo Injector Test facility at DESY, Zeuthen site). These results can be scaled to the proton bunch case to provide guiding for the AWAKE experiments. A first experimental run was conducted at PITZ in 2015 [4]. A novel cross-shaped plasma cell was constructed and successfully put into operation. After insertion of the plasma cell into the PITZ accelerator a series of experiments were run, but unfortunately no self-modulation of the electron beam was seen. Careful analysis of the experimental setup showed several shortfalls, preventing success. Based on this experience we started an upgrade of the components in question and here we report about this work.

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UPGRADES

The plasma cell of the PITZ experiment is a lithium heat pipe oven. Therefore we have two key component groups: the plasma cell itself with periphery and an ionization laser with a beam transport line. An ArF excimer laser (wavelength: 193nm) is used for direct ionization of the lithium.

Plasma Cell

Due to space restrictions in the PITZ beam line the standard heat pipe oven geometry was extended to a cross shape, utilizing the side arms for coupling the ionization laser light into the plasma cell [5]. This worked in principle – plasma was generated for the first time in such a geometry – but the lithium vapour density was only about 10^{14} cm^{-3}, two orders of magnitude below the target density. Two main reasons were found to cause that, both affecting the transport of the lithium in the plasma cell. The first reason was the design of the side arms: to stay flexible regarding the ionization laser the side arms were built in a funnel shape as shown in Fig. 1a. This shape enables the use of a high intensity Ti:sapphire laser for field ionization of the lithium. In order not to destroy the side windows it would be necessary to focus the laser beam into the metal vapour and at the same time to keep the laser intensity at the window positions below the damage threshold. But this geometry made cooling at the window end inefficient and the lithium vapour flow was not restricted efficiently in this direction, leading to lithium depositions at the plasma cell surfaces or even all the way through to the windows. Since we are now using only the ArF laser for ionization where we use a collimated beam, the side arms for the next generation plasma cell was designed to be straight, as shown in Fig. 1b. Since the cross section of the side arms is now very similar to those of the beam pipe, which worked well in the first proto-

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type, we expect no further problems with the lithium vapour transport.

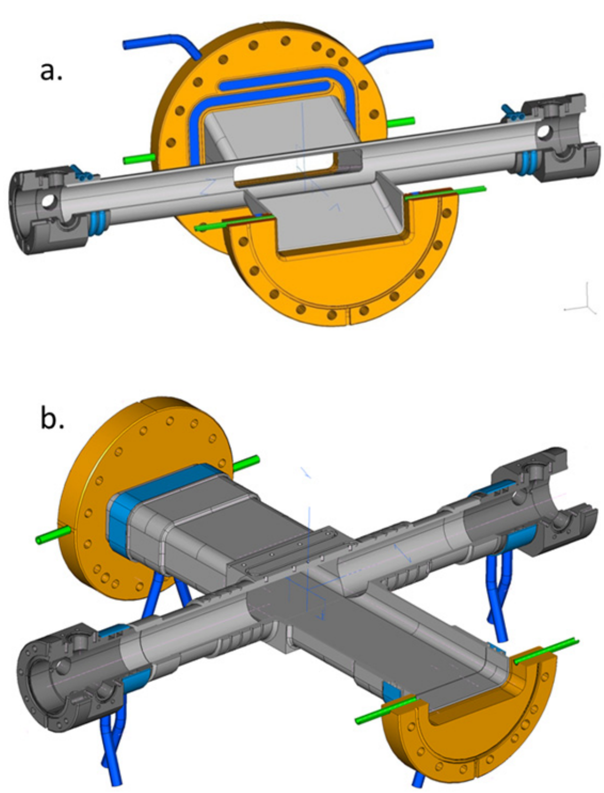

Figure 1: a.: Old plasma cell design with funnel shaped side arms. b.: New design with straight side arms and updated water cooling.

A second issue we had with the old plasma cell was the transport of the liquid lithium from the outer cell regions back to the hot zone. This was implemented with a mesh, which is placed against the inner pipe walls [6]. The function is based on capillary forces and as it turned out that the pores of the mesh which was used were too large. Due to insufficient transport lithium tended to solidify at the outer edges and accumulate there. This situation could be rectified easily by using a mesh with finer pores, but an additional difficulty is the complicated inner geometry of the cross shaped plasma cell which makes it difficult to cover all inner surfaces with the mesh. Several mesh parts are needed which are overlapping or touching at the edges, creating possible starting points for condensation. Therefore an alternative was tested to replace the mesh with grooves which are etched directly into the plasma cell walls. This was implemented first in a simple tube with results shown in Fig. 2. The grooves were etched into the whole inner diameter with groove width and distance of about 0.3 mm, the depth of the grooves is about 0.5 mm. Lithium was put into the test tube which was filled with argon buffer gas with a pressure of 0.3 mbar and heated afterwards up to 700°C. The lithium melted and by evaporation filled the grooves around the whole diameter, leading to a stable state. A long term test was started and after two weeks no lithium accumulation was seen, proving that these grooves can be used for transport of the liquid lithium. In the new plasma cell the grooves will be etched into the central pipes and both side arms, providing lithium transport in all sections.

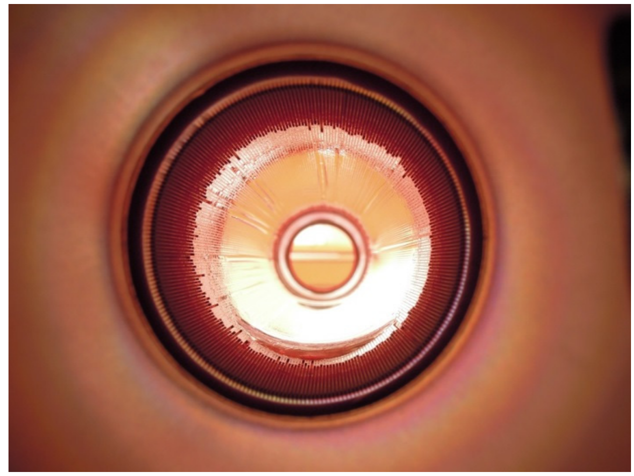

Figure 2: View into the test heat pipe oven with grooves. The hot part in the middle is evenly covered with lithium.

Another issue we had in the 2015 experimental run was the scattering of the electron beam when entering the plasma cell. To separate the atmosphere within the plasma cell from the vacuum in the accelerator beam tube windows are installed at the transition spots. Here a compromise is needed: the thinner the windows the less scattering of the electron beam but the higher the gas diffusion through the window. Additionally the mechanical strength of the windows decreases with the thickness, increasing the likelihood of damage. Due to their long radiation lengths and high elasticity, polymer foils were chosen as the window material. As reported before, the scattering of several material types was calculated, simulated and measured [4, 5]. The latest update of this effort is shown in Fig. 3.

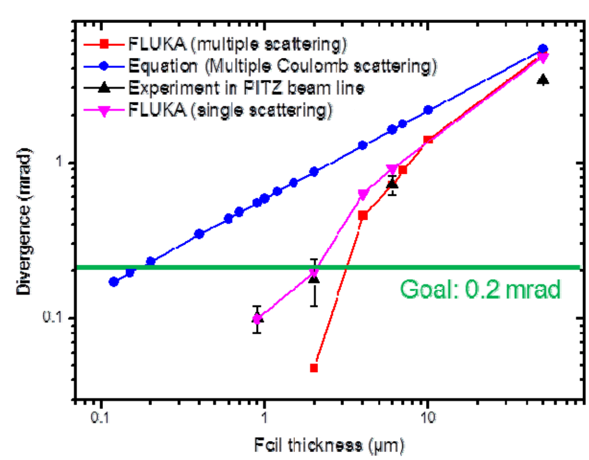

Figure 3: Calculated, simulated and measured scattering of 22 MeV electron beams at polymer foils [7].

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The equation (blue) is based on multiple Coulomb scattering, an assumption which breaks down for foil thicknesses of less than a few tens of micrometres. This is evident when comparing with the experimental results (black). The latter can be reproduced with FLUKA [8, 9] simulations, which are Monte Carlo simulations, especially when working with the single scattering option (pink). The goal for the PITZ experiment is to invoke a beam scattering divergence angle of less than 0.2 mrad [4], which can be achieved with a foil thickness of less than 2 µm. For the new plasma cell a 0.9 µm thick PET foil, which is covered on both sides with 37.5nm aluminium will be used. The metal coating reduces the gas permeation by sealing small pores which could form in the very thin foil.

Ionization Laser Beam Line

The ArF ionization laser is set up in a laser lab separated from the acceleration tunnel to prevent radiation damage and to have access to the laser during experiments. The laser beam has to be transported to the plasma cell over a distance of about 12 meters. The beam dimensions at the laser output aperture are 24x10 mm^2 with a divergence of 3x1 mrad^2. To prevent the increase of the beam size and its cutting at apertures along the beam line collimation and transport optics is needed. For the 2015 experimental run an optics box containing two spherical lenses was constructed. Due to the beam size and divergence differences in vertical and horizontal directions it is impossible to correct both axes exactly with simple spherical lenses. Beam transport was possible, but a significant fraction of the laser power was lost during transport. Therefore the system was re-evaluated in a ZEMAX simulation. A setup utilizing cylinder lenses was developed which allows undisturbed beam transport to the plasma cell. The optical system consists of four cylinder lenses (two for each axis) to allow optimal beam transport to be set for each axis. A sketch of the optical setup is shown in Fig. 4.

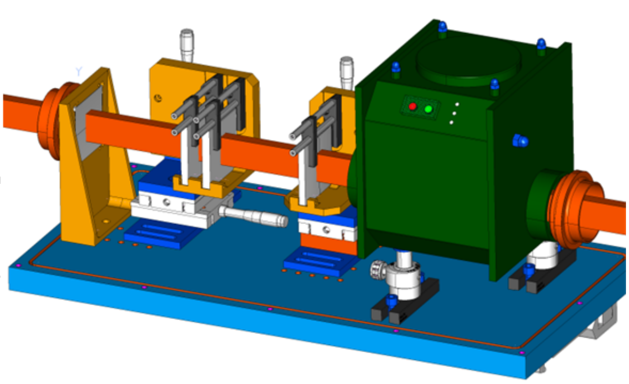

Figure 4: Sketch of cylinder lens setup for beam transport of ArF ionization laser. On the right side the laser safety shutter is shown.

Another improvement deals with the beam line itself: due to the short wavelength (193 nm) of the laser, it is not practical to send the light through normal atmosphere, since the light is strongly absorbed by oxygen. Therefore the laser light is guided through a nitrogen atmosphere inside a tubed beamline. The original beamline was leaky and led to strong power loss and thereby a low ionization rate of the lithium inside the plasma cell. The improvements for this year's experimental run include gas tight mirror assembly along the beam line and rubber bellows for connecting the mirror holders to the tubing in between. These gas tight bellows decouple the movements of pipes and mirror holders and in this way make alignment of the beam line much easier.

CONCLUSION

Upgrades to the experimental setup at PITZ were described with the goal to demonstrate the self-modulation instability of long electron beams in a lithium plasma this year. One key point for improvements is our novel cross-shaped plasma cell. The new design includes straight side arms and integrated grooves for better lithium circulation and thinner electron window foils for less electron scattering. The other main area of work is the ionization laser beam line with an improved optical setup for beam guidance and an enhanced mechanical setup to decrease transport losses. Taken together all these measures, we are confident to conduct a successful experimental run this year.

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