

NEXT GENERATION PLASMA CELL FOR PWFA EXPERIMENTS AT PITZ

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Abstract

A proof-of-principle experiment for the AWAKE experiment is ongoing at the Photo-Injector Test Facility at DESY, Zeuthen site (PITZ). The goal of the experiment is to observe and measure the energy and density self-modulation of a long electron beam passing through a laser-generated Lithium plasma [1]. Key devices of the experiment are a heat pipe based plasma cell, a photo-cathode laser system which enables production of long electron beams with sharp rising edges and well-developed diagnostics at PITZ, including a transverse deflecting cavity and a high-resolution electron spectrometer.

In this report, we present the current status of the experiment, including the latest updates of the experimental setup. The plasma cell is a lithium heat pipe oven with inert gas buffers at all input/output ports. An ArF ionization laser is coupled through side ports. Main improvements of the second generation plasma cell are an altered geometry of side arms and a new heat pipe design. Among other updates are an improved ArF laser beamline and new electron windows which introduce less scattering of the electron beam. We present here measurements of plasma density and homogeneity as well as results of beam transport studies for the experiment.

INTRODUCTION

Plasma wakefield acceleration is among the most promising technologies in accelerator physics, thanks to higher achievable acceleration gradients compared to conventional RF cavity based accelerators; harnessing it leads to a creation of compact and cost effective TeV scale accelerators in future [2].

In beam-driven plasma wakefield acceleration, to maximize the acceleration gradient, the length of the driver beam should match the plasma wavelength. The Advanced Wakefield Experiment (AWAKE) at CERN utilizes a high-energy proton driver beam [3], however, the beam is too long to achieve high magnitude acceleration fields. To overcome this problem, the experiment relies on the self-modulation instability (SMI) phenomenon – a separation of a long charged particle beam to shorter sub-beams in plasma [4]. The results of the self-modulation

experiment with an electron beam at PITZ can be scaled to the proton case and to provide valuable information for the AWAKE experiment.

First experiments with a novel cross-shaped plasma cell were conducted in 2015 [1], but no SMI of electron beam was observed. Due to imperfections of the plasma cell the goal plasma density was not achieved and the experiment was limited in time. A second plasma cell was designed considering shortcomings of the first setup [5]. Other aspects of the experiment, such as the ionisation laser beam transportation and electron beam matching in plasma, were reconsidered and improved, resulting first time-resolved measurements of self-modulations of electron beam in plasma [6]. This contribution presents an overview of the experimental setup and results of preliminary studies.

EXPERIMENTAL SETUP

Plasma Cell

The PITZ plasma cell is a cross shaped lithium heat pipe oven [7]. A homogeneous metal vapour column is formed in the heat pipe oven and then ionized by a laser. Due to space restrictions at PITZ, the ionisation laser is coupled through the side arms (Fig. 1). Argon buffers confine the lithium vapour in the centre of the plasma cell and protect its windows. The old plasma cell did not maintain enough circulation of lithium inside, resulting in depositions of solidified lithium in colder regions and in insufficient lithium vapour concentration.

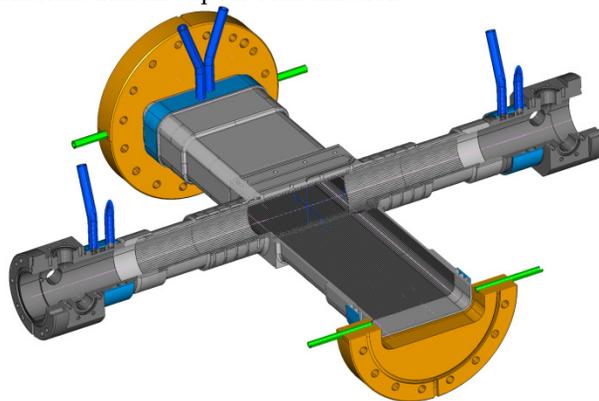


Figure 1: New plasma cell design with altered sidearms geometry and axial grooves etched on the inner surface.

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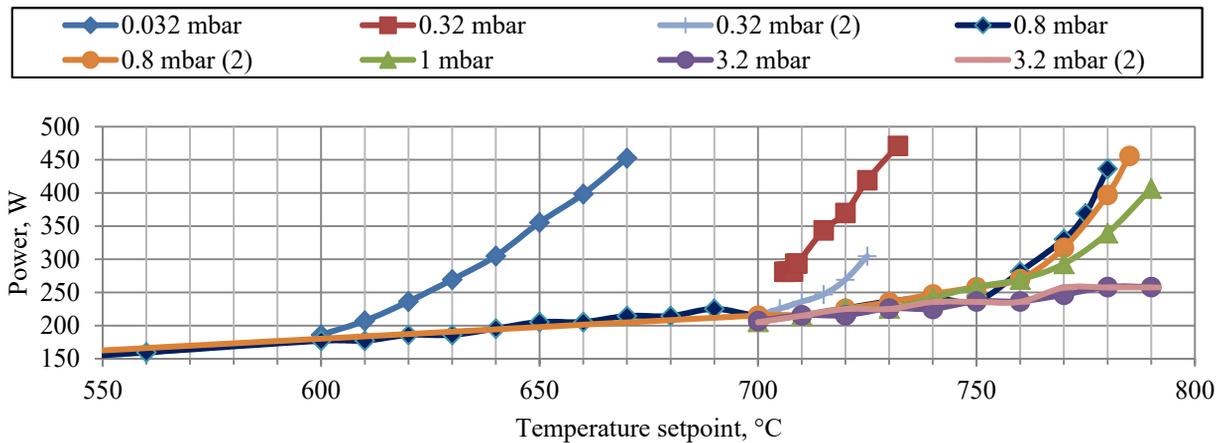


Figure 2: Temperature set point vs. heating power input for different buffer gas pressures.

Modifications introduced in the second design were aimed to improve the lithium transport and heat insulation of the plasma cell. In the old plasma cell a metal mesh placed on the inner surface of the plasma cell served as a wick for liquid lithium. The new design features axial grooves (the groove width and distance between grooves of about 0.4 mm, the groove depth of about 0.3 mm) etched in the walls of the main tube and the side arms. The lithium transportation with the grooves was studied with a simple tube test heat pipe oven has shown no issues. The same heat pipe setup was used to study the optimal buffer gas pressure. In a cold heat pipe oven, the whole volume of the oven is filled with the buffer gas. When heated, lithium melts and then evaporates at the temperature defined by the lithium vapour pressure curve for which the vapour pressure is equal to the buffer gas pressure. Continuously evaporated lithium displaces the buffer gas towards the colder regions and forms a homogeneous vapour column with a short transition region to the buffer gas. In the transition region lithium condenses and the liquid phase flows back under the action of capillary forces. If the heat pipe is heated to higher temperatures, the vapour column expands and compresses the buffer gas until new pressure equilibrium is found. In the oven mode, the heat pipe conducts large amounts of heat, so the power level can indicate if the oven mode is reached or not at given temperature and pressure levels. Figure 2 shows power-temperature dependencies for different buffer gas pressures in the test heat pipe. Kinks on the curves indicate transitions to the heat pipe oven mode. Space restrictions at the PITZ beamline put a limitation on the lower buffer gas pressure limit. The total lengths of the PITZ plasma cell main tube and the side arms are 50 cm and 44 cm, while the heat insulation length is about 32 cm along the main tube and 17 cm along the side arms. If the buffer gas pressure is too low, the transition between lithium vapour and the buffer gas will be not sharp enough, resulting in depositions of solid lithium in the cold regions and coating of the windows with a layer of lithium, which decreases the ionization laser transmission and, consequently, the maximum achievable plasma density. It was found that the windows coating does not occur

at a buffer gas pressure of 0.8 mbar. The line integrated lithium vapour density along the ionization channel was measured with the UV absorption method as described in [8] at this pressure. The vapour column length visually estimated to be about 25 cm. With this estimation measurements of the integrated density (Fig. 3), give a vapour density of about $3 \cdot 10^{15}$ - $3.8 \cdot 10^{15} \text{ cm}^{-3}$ at 705 °C. At this combination of buffer gas pressure and set point temperature the plasma cell is not in oven mode. To achieve better vapour density homogeneity, the plasma cell needs further heat insulation improvements and corresponding buffer gas pressure adjustments.

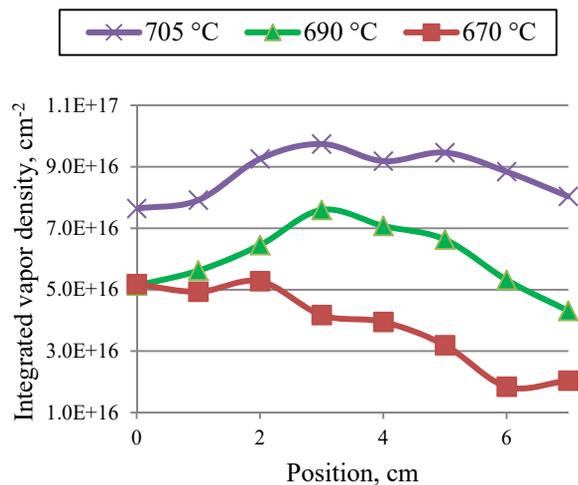


Figure 3: Linearly-integrated lithium vapor density measured along the ionization channel.

Ionization Laser and Laser Beamline

A Coherent COMPexPro 201 ArF laser is used for lithium vapour ionization. It is installed in a separate lab and an about 12-metre long laser beamline connects it with the plasma cell. The beam at the laser output has dimensions of $24 \times 10 \text{ mm}^2$ with divergence of $3 \times 1 \text{ mrad}^2$. A set of 4 cylindrical lenses is used to optimize the laser beam transport and prevent beam clipping on the beamline apertures. The wavelength of the laser is 193 nm, and the light is strongly absorbed by oxygen, therefore the laser

beamline was designed to be airtight and filled with nitrogen. During the 2015 experiments the beamline was leaky and required frequent flushing with nitrogen. Rubber bellows were proposed for connecting the beamline tubes with mirror holders as a measure to improve the gas tightness and mechanical stability of the laser beamline. However, the rubber degraded and disintegrated quickly under the exposition to UV light, so we had to keep rigid connections between the tubing and the mirror holders. As it was not possible to ensure proper air tightness of the beamline, during the experiments we had a so-called “controlled leak” – a constant low-intensity nitrogen flow through the beamline. To ionize the full length of the plasma column, the laser beam is stretched by means of two prisms installed in the optics box next to the plasma cell ionization port. After the final laser beamline alignment, the laser profile at the plasma cell position was measured at the plasma cell position in the tunnel (Fig. 4).

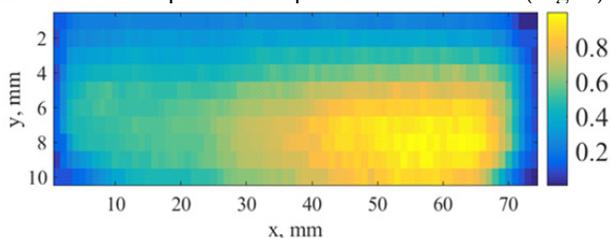


Figure 4: Normalized ionization laser intensity distribution along the plasma cell ionization window. The electron beam comes from the right side.

Electron Windows

Thin polymer foils are separating the plasma cell from the PITZ vacuum beamline. The foil windows must be thin enough to limit the electron beam scattering, but at the same time they must withstand pressure difference between the plasma cell and the beamline and limit the gas permeation from plasma cell to the beamline. In the 2016 experiment a $0.9\ \mu\text{m}$ PET foil coated on both sides with $37.5\ \text{nm}$ Al layers was used as the entrance window and an $8\ \mu\text{m}$ Kapton foil was used as the exit window. Simulations [1] and experiments in the beamline show a scattering angle of about $0.1\ \text{mrad}$, while the acceptable scattering for the experiment is $0.2\ \text{mrad}$. The foil durability against electron beam was studied during beam studies with a dummy plasma cell. The dummy plasma cell is a tube filled with the buffer gas to the nominal experimental pressure, terminated with the foil windows and installed at the plasma cell position in the PITZ beamline. Nominal beam transport conditions were applied (the beam was focused at the position corresponding to the beginning of the plasma column). The stress test included passing long

electron beam trains (1 nC, 250 bunches in the pulse train) through the dummy cell and demonstrated no significant change in gas permeation rate. A single 900 pC bunch was used later on in the SMI experiment.

CONCLUSION

Upgrades to the experimental setup enabled us to experimentally demonstrate self-modulation of a long electron beam in plasma. The new plasma cell design is a major improvement; however, the electron beam energy modulation period suggests that the maximum achieved plasma density was about $10^{14}\ \text{cm}^{-3}$. During the experiment, the plasma cell was not running in the oven mode, therefore there was an about 20% lithium vapour density deviation along the ionization channel. The lithium condensation issue was not completely resolved. Further improvements of the plasma cell insulation together with the fine tuning of the buffer gas pressure are needed to achieve higher plasma densities and more stable operation. For the next experiments the ionization laser beamline will be realigned to improve laser homogeneity. Thin metallized foil windows are completely satisfying the beam scattering and gas permeation requirements. The foils of the same thickness will be used in the next experiments.

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