DIELECTRIC LASER ACCELERATOR INVESTIGATION, SETUP SUBSTRATE MANUFACTURING AND INVESTIGATION OF EFFECTS OF LASER INDUCED ELECTROMIGRATION RF CAVITY BREAKDOWN INFLUENCES*

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Abstract

Dielectric laser acceleration (DLA) where the high electric fields in lasers are used to accelerate electrons next to nanofabricated dielectric structures has recently been proven in proof of concept studies. In this paper we describe the investigatory setup including a laser system prepared at a scanning electron microscope (SEM) for investigations into DLA and vacuum breakdowns occurring at radiofrequency (RF) accelerating structures. The method for manufacturing substrate for DLA is also presented.

INTRODUCTION

Accelerator physics plays an increasingly important role in many research fields within the natural sciences [1]. The related infrastructure is known for being spacious and expensive. The particle acceleration is made by strong electric fields where electrical breakdown inside of the metallic structures typically limits the gradient to 10-50 MVm^{-1} [2]. Current state of the art are normal-conducting copper structures developed over the years by the Compact Linear Collider (CLIC) collaboration that can reach gradients of 100 MVm^{-1} in stable operation [3]. To significantly increase this limit, we need to search for new technologies.

Dielectric materials show an unsurpassed ability to sustain high electric fields and dielectric laser acceleration (DLA) is the technique where the strong electric fields from laser beams in conjunction with nanofabricated dielectric structures are used for acceleration of charged particles [4]. It has been demonstrated in proof of principle studies for electrons ranging from the non-relativistic region [4,5] to relativistic [6]. Currently acceleration gradients up to 690 MVm^{-1} have been demonstrated but the technology is expected to reach above 1 GVm^{-1} in the near future [7].

DLA is under strong development and challenges exist such as finding optimal dielectric material, structural shape and timing the laser pulse with the electron beam. In this paper we address tests with flat polycrystalline diamond substrates, manufacturing of gratings, construction of a test setup as well as description on how this setup can be used for investigations into vacuum breakdowns occurring at high electric fields in metallic accelerator cavities.

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TEST SETUP CONSTRUCTION

Acceleration of low energy electrons is arguably one of the most important steps to take in the DLA context. As an ideal test bench and with inspiration from FAU we choose to design a first Swedish test bench based on a SEM.

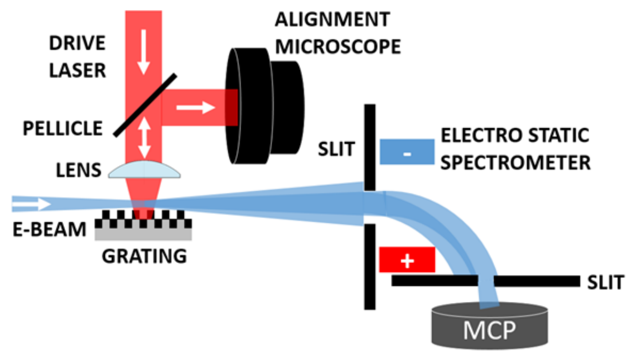

Figure 1: Schematic of setup with electron beam deriving from SEM, acceleration at grating and electro static spectrometer for characterisation.

SEM Setup

As depicted in Fig. 1 the electron beam is passing close to a dielectric grid and is affected from near fields excited by the transversely directed laser. The position of the laser spot on the grating is read out by an alignment microscope. The effect of the acceleration is investigated by a spectrometer based on electrostatic plates bending the trajectory of the electron beam before impinging on a micro channel plate (MCP).

A Philips XL-30 Field Emission ESEM was selected as best suited for DLA experiments (Fig. 2) out of the six existing scanning electron microscopes at the Ångström clean room. The interior volume of ~Ø300x200 mm is sufficient for implementation of XYZ manipulation stage as well as the electrostatic spectrometer. Additionally, the sample stage can be replaced by a custom made variant with implemented ion pump for further suppression of residual gas pressure.

The XYZ manipulation stage has <1 nm resolution to ensure sufficient handling inside of the setup [Fig. 3]. It is based on three stacked Smaract SLC1720 vacuum compatible linear piezo stages mounted on a support setup designed at the Ångström Laboratory and can be additionally adapted for the experiments.

Grating Manufacturing

Optical quality polycrystalline diamond substrates 10 mm diameter and 300 µm thickness is used for the diamond grating fabrication (Element Six Ltd. and Diamond Materials GmbH). Recently an improved process for fabrication was demonstrated by co-authors utilizing electron-beam lithography, nano-replication using solvent assisted micro molding (SAMIM) [8,9], and inductively coupled plasma etching (ICP-RIE) of Al, Si and diamond. The process result in diminishable line width differences compared to master grating pattern. Thanks to pure oxygen chemistry during the ICP-RIE step of diamond a lower sidewall angle was demonstrated [8]. The diamond gratings will be tested at the DLA setup at FAU, Erlangen, Germany.

Figure 2: Installation of lasers in front of SEM at the Ångström Laboratory clean room.

Laser Setup

A Spectra Physics Tsunami Ti:Sapphire laser at Ångström laboratory is used for the experimental setup in Sweden. The wavelength is within 720-850 nm, average power is >0.7 W, pulse width <100 fs and repetition rate of 80 MHz. The peak field can therefore be calculated to ~800 MVm^{-1} which is sufficient for the foreseen investigations. The laser beam will be directed through a periscope, passed through an anti-reflective coated viewport into the SEM and focused onto the acceleration grating by a positive lens. To ensure impinging on the right spot on the grating an extra lens mounted on a manual XY-micrometer stage outside of the SEM is used for position control and feedback is given through the reflected light from a beam sampler and subsequently read out by a microscope (see Fig. 1).

LASER DAMAGE TESTS

A first step in investigating new grating material for suitability for the task is investigation of laser damage threshold. Polycrystalline diamond substrates of optical quality (Diamond Materials GmbH and Element Six Ltd.) with a diameter of 10 mm and a thickness of 300 µm was irradiated by a laser with 1.93 µm wavelength, pulse duration of 600 fs and repetition rate of 1 MHz in Erlangen. The laser pulses with peak field of E=4 GV/m were not causing any visible damage to the diamond sample. This motivates a continuation using diamond substrates and the subsequent steps of grating manufacturing.

SURFACE CHARACTERIZATION THROUGH LASER INDUCED ELECTROMIGRATION INVESTIGATIONS

The CLIC uses normal-conducting, high-gradient copper accelerating structures [3] and due to the high gradient of 100 MVm^{-1}, breakdown of the radio-frequency fields (RF) is an issue and a limiting factor for achieving high luminosity. There are many aspects of RF breakdown (BD), vacuum discharges, conditioning and field-emission that are not fully understood.

The classical BD theory, where BD onset starts at a local surface defect, assumes that the electric field is enhanced at the defect location and can become sufficiently high to start field emission from the nano-protrusion. What follows is heating of the material, evaporation of the neutrals and ionization by field emitted electrons resulting in formation of plasma and finally of an arc. There are alternative scenarios to classical theory that suspect that a form of electromigration also takes place [10].

Electromigration which is a type of mass transport process in solids under influence of electric field has strongest effect at the surface and along the grain boundaries and is enhanced with the presence of bulk defects like dislocations. When an electric field is high enough atoms tend to migrate along field gradient in a collective motion. It is theorized that the repetitive action of a RF field can cause formation of an array of nano-protrusions from the bulk material.

We have a setup for in-situ SEM studies of electrical discharges where a metallic sample and a tungsten tip are mounted on the movable stage driven by piezo-motors (Fig. 3) [11]. This allows for precise control of the gap distance between the tip and surface and location on the surface. High voltage is applied over the gap and with a Keithley electrometer 6517A the field emission currents can be measured. The setup allows for studies of surface changes due to field emission under DC field, however exact correlation of the results with situation in RF is not fully possible. With the laser setup described earlier we now have the possibility to study various laser-induced discharge phenomena. Interesting effects of laser-induced

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faceting and growth [12] have been studied before and the importance of electromigration in the context of accelerating structures has been pointed out [10].

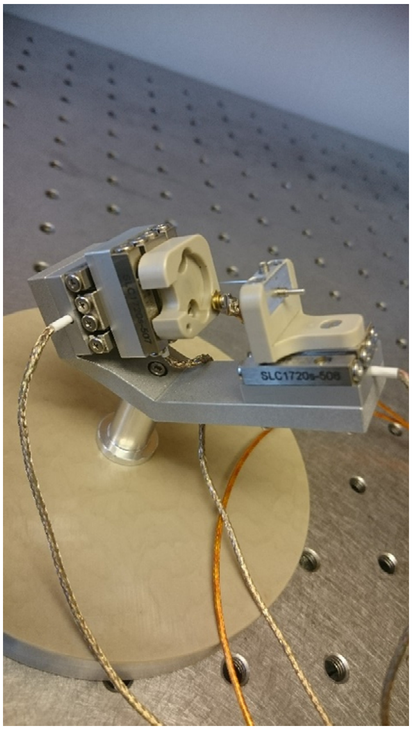

Figure 3: XYZ-control through nm resolution linear piezo stages and tungsten tip.

CONCLUSION

Accelerator physics is a heavily expanding field where more effective acceleration devices are needed. A promising method is DLA which is demonstrated but needs further development. A suitable test source is a SEM as used in FAU. This setup will be used for tests of new material evaluated for the purpose such as polycrystalline diamond gratings. An additional test setup is currently built up in Sweden and will also be used for laser induced electromigration studies.

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