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# DIELECTRIC LASER ACCELERATION SETUP DESIGN, GRATING MANUFACTURING AND INVESTIGATIONS INTO LASER INDUCED RF CAVITY BREAKDOWNS\*

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## Abstract

Dielectric laser acceleration (DLA) is the technique utilizing strong electric fields in lasers to accelerate electrons in the proximity of nanoscaled dielectric gratings. The concept was recently demonstrated in experimental studies. Here, we describe the experimental DLA investigation setup design including laser system and scanning electron microscope (SEM). We also present the grating manufacturing methods as well as investigations into vacuum breakdowns occurring at RF accelerating structures.

## INTRODUCTION

Accelerator physics plays an exponentially increasing role within the fields of natural sciences though the technology is generally spacious and expensive which hampers scientific progress [1]. Electrical breakdown inside of the acceleration cavities are limiting them in field strength and, therefore, size. Typical gradients are on the order of 10-50 MVm<sup>-1</sup> [2], which is less than the structures developed by the Compact Linear Collider (CLIC) collaboration, which operate up to 100 MVm<sup>-1</sup> [3]. To overcome these limits, alternative methods should be investigated.

Dielectric materials have proven superior properties regarding damage threshold of strong electric fields. Therefore, dielectric laser acceleration (DLA) where the strong electric fields from lasers are used for acceleration of charged particles at nanofabricated dielectric structures is a promising alternative [4]. The method has recently been proven in proof of principle studies for a large interval of energies ranging from non-relativistic and with acceleration gradients up to 690 MVm<sup>-1</sup> [4-7].

The technology is under development and promising, with gradients 10-100 times higher than current state of the art. Such increase in gradients would result in the corresponding size reduction and effectively more inexpensive accelerators rendering in higher scientific output when more accelerators can be built up. Challenges include timing, manufacturing of the dielectric structures regarding material and layout.

In this paper, we describe manufacturing of acceleration gratings made of diamond, construction of an acceleration test setup and how this setup can be utilized for vacuum breakdowns by high electric fields in metallic accelerator cavities (this is also previously described in [8]).

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## DIAMOND GRATING MANUFACTURING AND LASER DAMAGE INVESTIGATIONS

For the dielectric acceleration grating structures we choose to work with 10 mm diameter and 300 μm thick polycrystalline diamond substrates from Element Six Ltd and Diamond Materials GmbH.

Recently, co-authors demonstrated an improved process utilizing electron-beam lithography, nano-replication using solvent assisted micro molding (SAMIM) [9,10]. The result of this process are replicas with line widths close to identical to the master grating pattern. The method furthermore includes inductively coupled plasma etching (ICP-RIE) with pure oxygen resulting in a lower sidewall angle [9].

As a first suitability test laser damage investigations of unprocessed diamond substrates were undertaken Friedrich-Alexander Universität (FAU) in Erlangen, Germany. The substrates were irradiated by a 1MHz laser with a wavelength of 1.93 μm, 600-fs pulse duration, and a 4-GVm<sup>-1</sup> peak field. No visible damage on the substrates was identified which motivated proceeding with the subsequent manufacturing steps.

Once the diamond structures are ready they will be tested for acceleration at FAU.

## SEM TEST SETUP

We are constructing a DLA test bench based on a scanning electron microscope (SEM) Philips XL-30 (Fig. 1), with a similar design as at FAU. Such device can provide a well determined and precisely tuneable electron beam. Furthermore, the electron energies are typically in the tens of keV which arguably a very important energy range for investigation.

The design scheme in Fig. 2, illustrates where the electron beam passes near the acceleration grating. A laser beam is irradiating in transverse direction, exciting near fields which accelerate electrons in the right phase. An alignment microscope is used to read out the position of the laser spot on the diamond grating. Finally, an energy spectrometer is used for reading out the effect of the acceleration. It consists of two electrostatic plates bending the electron beam onto a micro channel plate (MCP).

The inside of the SEM of ~Ø300x200 mm leaves room for movable sample mount and energy spectrometer. The sample mount consists of three vacuum compatible



Figure 1: Installation of lasers in front of SEM at the Ångström Laboratory clean room.

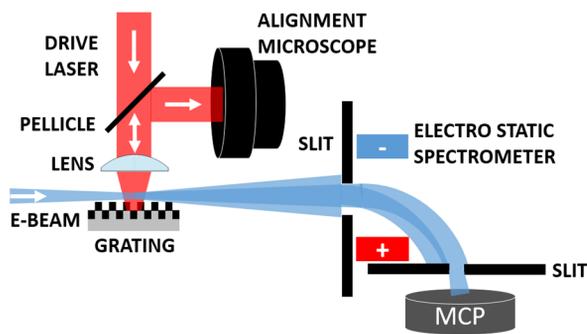


Figure 2: Design scheme of the DLA test setup. The electron beam is emitted from a SEM and is then subsequently passing the acceleration grating and an energy spectrometer.

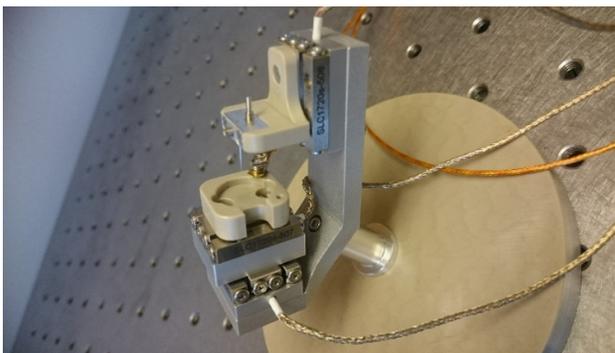


Figure 3: XYZ-control through nm resolution linear piezo stages and tungsten tip.

Smaract SLC1720 linear piezo translation stages as shown in Fig. 3. Each stage has better than 1-nm resolution and the sample mount can be further adapted at the Ångström Laboratory workshop for the forthcoming experiments.

### LASER SETUP

The experimental setup includes Spectra Physics Tsunami Ti:Sapphire laser used for the acceleration. It runs with 80 MHz repetition rate, wavelength of 720-850 nm, better than 100-fs pulse duration, and with a peak field of approximately  $800 \text{ MVm}^{-1}$ .

The emitted light passes a periscope, vacuum viewport into the SEM where a positive lens is used to focus the beam onto the acceleration substrate. An additional positive lens mounted on a XY manual micrometer translation stage is used to direct the beam after reading out the position on an alignment microscope from a part of the reflected light, as shown in Fig. 2.

### SURFACE HARDENING THROUGH LASER INDUCED CONDITIONING

CLIC uses normal-conducting, high-gradient copper accelerating structures [3] and due to the high gradient of  $100 \text{ MVm}^{-1}$ , 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 e.g. a nano-protrusion or a scratch on the surface, assumes that the electric field is enhanced at the defect location and can become sufficiently high to start field emission from that site. 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.

The results from conditioning of the high-gradient RF structures show that situation is even more complicated. This mechanism can explain the behaviour at lower field values, but when structure is reaching surface fields well above  $100 \text{ MVm}^{-1}$  it is believed that a more ultimate physical limit is reached. At these fields one starts to see evidence of field generated features not just on the surface but rather forming below the surface and being connected with dynamics of dislocations, which are imperfection of the crystal lattice that are being generated and are moving around due to operated field. Evidence indicates that the conditioning is a pulse-by-pulse process, depending not on the number of RF breakdowns but rather the total number of RF pulses [11].

It is therefore theorized that the repetitive action of a RF field forms an array of new dislocations that move and interlock with each other reducing the possibility of further movement within the bulk. Only when this happens the breakdown rate reduces to sufficiently low levels as required by CLIC [12].

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) [13]. 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 laser-induced conditioning phenomena which perhaps can resemble situation with RF more closely. Interesting effects of laser-induced faceting and growth [14] have been studied before and the importance of collective motion inside crystal lattice in the context of accelerating structures has been pointed out [15].

## CONCLUSION

The field of accelerator physics is expanding strongly and more efficient acceleration cavities are needed for a faster and less expensive scientific progress. DLA is an attractive concept which recently was demonstrated, and should be further investigated and developed. We are designing diamond gratings which will be tested at the FAU SEM test setup and subsequently in Sweden on a new setup built up at Uppsala University. This setup can also be used for investigation towards laser induced conditioning of the metallic surface.

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