BEAM-CHARGE DIAGNOSTICS IN LASER-PLASMA ACCELERATORS WITH DIAMOND DETECTORS*

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Abstract

Accurate measurement of shot-to-shot fluctuations in electron beams produced by laser-plasma accelerators (LPAs) is important for their development. Reliable monitoring of beam reproducibility and stability is crucial for accelerator operation. However, the high peak current and electromagnetic pulse environment make beam diagnostics challenging. In this work, preliminary results of bunch charge measurements using a diamond detector in an LPA environment are presented. A dedicated sCVD diamond detector was installed at the Lund High-Power Laser Facility. The average electron bunch charge was measured via a transverse beam scan. The measurement results are discussed, and an outlook on the development of diamond-based beam diagnostics and dosimetric applications for LPA facilities will be given.

INTRODUCTION

This work presents the first single-shot measurements of bunch charge using a thin single-crystal chemical vapor deposition (sCVD) diamond detector at the Lund-High Power Laser Facility. Results from the experimental campaign include transverse one-dimensional beam scans and bunch-charge measurements. The experiments further provide insight into beam reproducibility, shot-to-shot fluctuations, and pointing stability.

Laser-plasma accelerators (LPAs) are next-generation particle accelerators, producing accelerating field gradients of tens of GeV/cm. The inherently large shot-to-shot variations arise from the nonlinear nature of the acceleration process. As a result, LPAs exhibit broad energy spectra, mrad-level divergences, fluctuations in bunch charge, and suffer from pointing instability [1]. Their high-intensity, femtosecond electron bunches produce high peak currents in laser-plasma accelerators, introducing challenges for beam diagnostics. A key challenge is the absolute measurement of bunch charge. Conventional integrators and current transformers suffer from saturation, nonlinear response, and electromagnetic pulses (EMPs) interference [2]. sCVD diamond detectors are promising because they combine radiation hardness, fast response, and linear charge collection at high instantaneous ionization. Diamond detectors' wide bandgap (5.48 eV) suppresses photoionization, and their sub-nanosecond charge collection produces signals that are separated from slower, nanosecond-scale EMPs [3].

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EXPERIMENTAL SETUP

The experimental campaign was carried out at the Lund High-Power Laser Facility using LUCID, a multi-terawatt OPCPA laser system [4–6]. Electron injection was driven by a laser-plasma interaction using a 9.5 fs, 175 mJ laser pulse focused to an 11 µm spot. The interaction employed ionization injection using an $f/9$ off-axis parabolic mirror which focused the beam into a supersonic gas jet target consisting of a helium-nitrogen mixture. The jet emerged from a 1.5 mm pulsed nozzle, with the focus set 2.2 mm above the orifice. The facility is equipped with a dipole magnet spectrometer coupled to a Lanex scintillating screen for measurements of the electron beam energy.

A 43 µm single-crystal chemical vapor deposition (sCVD) diamond detector with an active area of 4 mm × 4 mm was used for the measurements [7]. A bias voltage of 50 V, corresponding to 1.2 V/µm was applied. The detector response was recorded using a PicoScope 6000E series oscilloscope. It has a 5 GSPS sampling rate, 250 MHz analog bandwidth, 8-bit vertical resolution and 50 Ω input impedance. No amplifier was used because of the high peak currents.

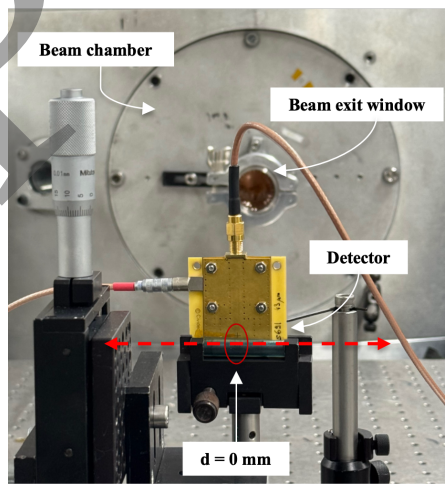

Figure 1: The sCVD diamond detector mounted the on LPA beamline, 82 cm downstream of the Kapton exit window.

The laser-plasma wakefield generated electron beams propagated through 126 cm of vacuum up to the Kapton window. The detector was mounted on a motorized translation stage 82 cm downstream of the beam exit Kapton window shown in Fig 1. At this distance, the electron beam has expanded significantly due to its divergence, such that the transverse beam size exceeded the size of the diamond sensor. To reconstruct the beam's one-dimensional spatial distribution and the transverse bunch charge profile, a hor-

izontal scan was performed. The detector was translated laterally from $d = -35$ mm to 30 mm in 5 mm increments, with $d = 0$ mm corresponding to the beam axis. All other positions denote transverse offsets from this reference.

A Lanex-based spectrometer was used to characterize electron beam quality and energy prior to diamond measurements. Electrons were first directed to the Lanex screen to record a few shots before being sent to the diamond detector at each scan position. The produced electron bunches have an average energy of 40 MeV. The Lanex spectrometer and the diamond detector could not be used simultaneously due to mechanical constraints.

BUNCH CHARGE DETERMINATION

High-energy electrons deposit only a small fraction of their kinetic energy within the active volume of the diamond detector, enabling a minimally invasive measurement. The energy deposited by a single electron is estimated using the stopping power $S(40\,\text{MeV}) = 0.6\,\text{keV}\,\mu\text{m}^{-1}$ and the detector thickness $d = 43\,\mu$m, yielding $E_{\text{dep}} = 25.8$ keV [3]:

$$E_{\text{dep}} = S(E) \cdot d \tag{1}$$

The number of electron–hole pairs generated per incident electron is given by

$$n_{eh} = \frac{E_{\text{dep}}}{e_i} \tag{2}$$

where $e_i = 13$ eV is the mean energy required to create a single electron-hole pair in diamond [8]. The charge produced by a single traversing electron is

$$Q_e = n_{eh} \cdot e \tag{3}$$

where e denotes the elementary charge. The total collected ionization charge is determined by integrating the measured voltage signal $V(t)$ across the input impedance R:

$$Q_{\text{ion}} = \frac{1}{R} \int V(t) \cdot dt \tag{4}$$

A charge-collection efficiency of 100% is assumed for thin sCVD diamond detectors at the applied electric field. The number of electrons as bunch intensity is calculated as:

$$n_{\text{bunch}} = \frac{Q_{\text{ion}}}{Q_e} \tag{5}$$

And the corresponding bunch charge is given by

$$Q_{\text{bunch}} = n_{\text{bunch}} \cdot e \tag{6}$$

In addition, the measured ionization charge Q_{ion} can be converted to the absorbed dose D using the formula:

$$D = k \cdot Q_{\text{ion}} \tag{7}$$

where $k = 5.8{\times}10^9$ mGy C^{-1}. This proportionality constant is derived from the ionization energy (e_i), the density of diamond ($\rho = 3.51$ g cm^{-3}) and the sensitive volume of the detector.

RESULTS AND DISCUSSION

Shot-to-shot Detector Response

Figure 2 shows the detector's raw intrinsic response for individual shots at $d = 5$ mm. Here, the hightest peak amplitude across the input impedance corresponds to an instantaneous current of 200 mA. The pulse shape was stable, with a FWHM of (1.6 ± 0.03) ns.

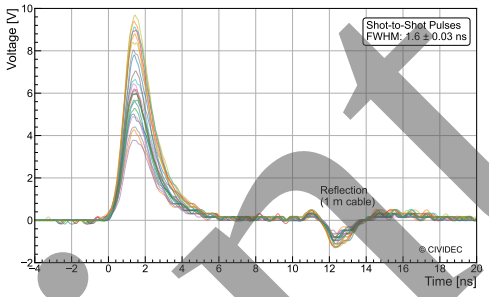

Figure 2: Raw pulses recorded for 50 consecutive shots at beam axis offset of $d = 5$ mm.

The recorded pulses show clean single-shot signals from the sCVD diamond detector. The results demonstrate its capability to record bunches with high peak current. The consistent FWHM and shape reflect the linear intrinsic temporal response of the detector to femtosecond electron bunches with high peak current. The sequence of consecutive shots further illustrates the high stability and reproducibility of the detector response.

Transverse Beam Profile Scan

A transverse scan was performed by translating the diamond detector in 5 mm steps across the beam. At each step, 50 consecutive shots were recorded on a shot-by-shot basis to reconstruct the 1-d spatial profile. The peak amplitudes for each pulse, corresponding to individual shots, are shown in Fig 3.

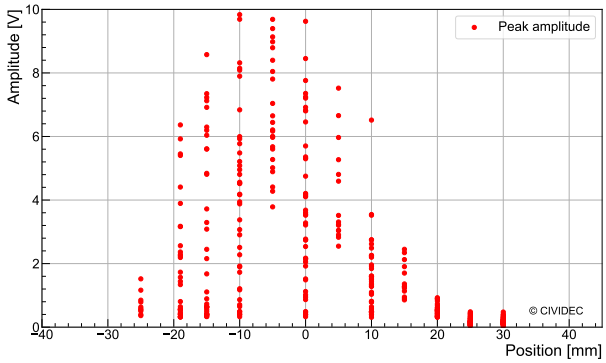

Figure 3: Distribution of pulse peak amplitudes as a function of detector transverse position.

The data show that the highest amplitudes occur at an offset of $d = -5$ mm, indicating that the beam is predominantly shifted from the geometric center at $d = 0$ mm. This shift indicates that the electron beam pointing, caused by

the laser-plasma interaction and subsequent transport, deviates from the mechanical beam axis. As each shot arises from an independent laser-plasma interaction, the data inherently reflects the stochasticity of the beam's trajectory and stability [1, 2, 5].

Beam Charge Spatial Profile

To translate the spatial scan into a physical measure of beam intensity, the recorded pulse amplitudes were converted into bunch charge at each position. This reconstruction, shown in Fig 4, represents the one-dimensional spatial profile of the electron beam as measured at the diagnostic plane.

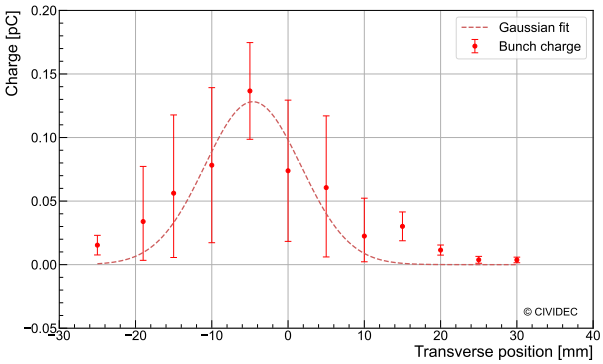

Figure 4: Measured beam charge profile as a function of detector transverse position.

Each data point represents the mean charge measured by the diamond detector over multiple pulses at a given position. Error bars are derived from the standard deviation of the pulse-to-pulse charge distribution, illustrating the shot-to-shot fluctuations in bunch charge.

The beam spatial profile is fitted with a Gaussian with a FWHM of 14.86 mm. The results provides a quantitative measure of the beam's spatial extent, reaching a peak bunch charge of 0.14 pC at the center. At the same position, the measured absorbed dose is $D = 0.81\,\mu\text{Gy}$.

OUTLOOK

Future experiment will focus on in-vacuum, absolute charge measurements by positioning the diamond sensor closer to the interaction point. The smaller beam footprint will allow the detector's active area to capture the entire electron beam. To accommodate the high peak currents generated by these ultrashort electron bunches, the detector will be integrated with an impedance-matched shunt readout. This configuration enables real-time, simultaneous determination of absolute bunch charge and absorbed dose with improved accuracy.

CONCLUSION

This experimental work demonstrates the use of sCVD diamond detectors for real-time, minimally invasive monitoring of femtosecond electron bunches with ultra-high instantaneous current from laser-plasma accelerators. The presented results are the baseline for future experiments, with a diamond detector integrated with shunt readout for in-vacuum, single-shot characterization of instantaneous high-intensity electron bunches. These preliminary results underline the dosimetric application of diamond detectors high-dose-rate radiation monitoring in extreme particle flux environments. This diagnostic approach directly addresses the critical need within EuPRAXIA for high-precision, ultrafast beam diagnostics.

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