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Recent Demonstration of Record High Gradients in Dielectric Laser Accelerating Structures

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Abstract. Recently, record high accelerating gradients have been demonstrated in dielectric laser accelerator structures. However, the temporal profile and phase of compressed femtosecond laser pulses often deviates from theoretical distributions. In this work, we apply frequency-resolved optical gating to interpret the peak accelerating gradient in experiments with relativistic beams in dielectric laser accelerators, highlight recent experimental results and outline the scope for future increases in accelerating gradient in dielectric laser accelerator structures.

INTRODUCTION

Several applications of accelerators call for significantly higher accelerating gradients than provided by conventional normal-conducting or superconducting linear accelerators. Significant increases in accelerating gradient have the potential to enable compact radiotherapy devices [1, 2] and free-electron lasers [3, 4]. In particular, proposed multi-TeV scale electron-positron linear colliders demand average accelerating gradients >1 GV m^{-1} [5]. Dielectric laser accelerators (DLAs) are one potential technology for high accelerating gradient, high energy efficiency linear electron accelerators, fabricated using established techniques in the semiconductor industry and powered using energy-efficient solid state lasers [6, 7, 8].

Recently, DLA experiments using subrelativistic and relativistic electron beams have demonstrated record-high accelerating gradients. Femtosecond laser pulses can be employed in order to achieve the desired GV m^{-1} accelerating gradients without damaging the dielectric microstructure, however, the temporal profile of such pulses often deviates from ideal Gaussian distributions. In this work, we outline a method to determine the peak accelerating gradient from measured femtosecond duration laser pulses with arbitrary temporal amplitude and phase, highlight several recent results, and outline scope for future increases in accelerating gradient.

PRIOR ART

The first acceleration of relativistic electrons in a DLA at SLAC demonstrated an accelerating gradient of 309.8 ± 20.7 MV m^{-1} [9]. In that experiment, ps duration laser pulses were used. However, there is a plateau in the single-pulse damage threshold for fused silica below ~ps pulse duration [10]. Hence, operation of a DLA at the highest electric (accelerating) field implies operating with the shortest laser pulse duration, for a given pulse energy. By reducing

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the incident pulse duration to 72 fs, a peak accelerating gradient of 690 ± 100 MV m^{-1} was recently observed in experiments with relativistic beams in a DLA at SLAC [11].

Since the first demonstration of acceleration of subrelativistic electrons in a single grating DLA at Erlangen [12], there have been several experimental demonstrations of acceleration with significantly increased accelerating gradient. Using a silicon grating, an acceleration gradient of 218 ± 20 MV m^{-1} was demonstrated in experiments with subrelativistic electrons at Stanford [13].

Recently an accelerating gradient of 376 ± 40 MV m^{-1} was demonstrated in a dual pillar structure with subrelativistic electrons at Stanford [14]. The function of the dual pillar structure is conceptually similar to the dual grating structure [15], except that monolithic fabrication results in ideal longitudinal alignment of the two rows of pillars. With appropriate optimization of the pillar geometries, an accelerating mode with a cosh-like transverse profile was demonstrated. Operating in this mode, the field profile (and accelerating gradient) do not decay exponentially with distance from the grating surface, and so the acceleration gradient is closer to uniform across the width of the acceleration channel.

INTERPRETATION OF PEAK GRADIENT

In DLA experiments, a dielectric microstructure is used to modulate the phase of an incident laser pulse to accelerate electrons. Of particular interest is the interpretation of peak accelerating gradient in experiments using short (fs) laser pulses. In previous DLA experiments, the laser pulse duration was measured using autocorrelation, and the pulse profile assumed to be Gaussian [9, 12, 13, 14]. Under such an assumption, the peak accelerating gradient, G, can be expressed as [16]:

$$G = \frac{\Delta E}{q w_i \sqrt{\pi}}, \tag{1}$$

where ΔE is the energy gain of the electron in the DLA, q is the electron charge, and w_i is the interaction length. For a laser pulse with a Gaussian temporal distribution and a Gaussian spatial extent across the structure, the interaction length, w_i, can be expressed by [16]:

$$w_i = \left(\frac{1}{w_l^2} + \frac{2 \log_e 2}{(\beta c \tau_i)^2} \right)^{-1/2}, \tag{2}$$

where w_l is the Gaussian beam radius of the laser beam intensity ($1/e^2$ of peak), c is the speed of light in vacuum, the electron velocity $\beta = v/c$, and τ_i is the full-width at half-maximum duration of the Gaussian laser pulse intensity envelope.

However, the temporal profile of ultrafast laser pulses produced by regenerative amplifiers often deviates from ideal Gaussian distributions, as was the case in the experiment in Ref. [11]. Hence, we seek to define the peak accelerating gradient in terms of [11]:

$$G = \frac{\Delta E}{\Delta E_l} \times \left(1 \text{ GV m}^{-1} \right), \tag{3}$$

where ΔE_l is the energy gain in a DLA over the interaction with an arbitrary laser pulse. The energy gain, ΔE, can be measured in experiments by dispersing the electron energy spectrum at a bending magnet spectrometer [11].

Frequency resolved optical gating (FROG) is one technique for the characterization of ultrashort laser pulses [17, 18]. One particular realization of this technique is the grating-eliminated, no-nonsense observation of ultrafast incident laser light E-fields (GRENOUILLE) [19]. The incident laser field is split and interfered at a thick nonlinear crystal for second-harmonic generation (SHG). The measured interferogram can be fitted to determine the temporal and spectral amplitude and phase of the incident laser pulse. An example measurement of a laser pulse with a non-Gaussian temporal distribution is presented in Fig. 1.

As outlined in Eq. (3), we seek to determine ΔE_l, the electron energy gain in a DLA resulting from an interaction with a measured laser pulse as presented in Fig. 1. DLA structures are designed to operate with a linear dependence between the incident laser electric field and the accelerating gradient. In addition to electromagnetic simulations of DLA devices [20], this linear dependence has been established in several recent experiments [9, 13, 14]. Hence, the accelerating gradient, G, is proportional to the measured amplitude of the incident electric field. To determine the peak gradient, we consider the temporal amplitude and phase of the laser pulse, which is plotted in Fig. 2.

In order to determine the energy gain, ΔE_l, the accelerating gradient, G, is integrated over the duration of the laser pulse. If it is assumed that there is no phase variation across the pulse (Fig. 2, $A(t)$), the maximum energy gain

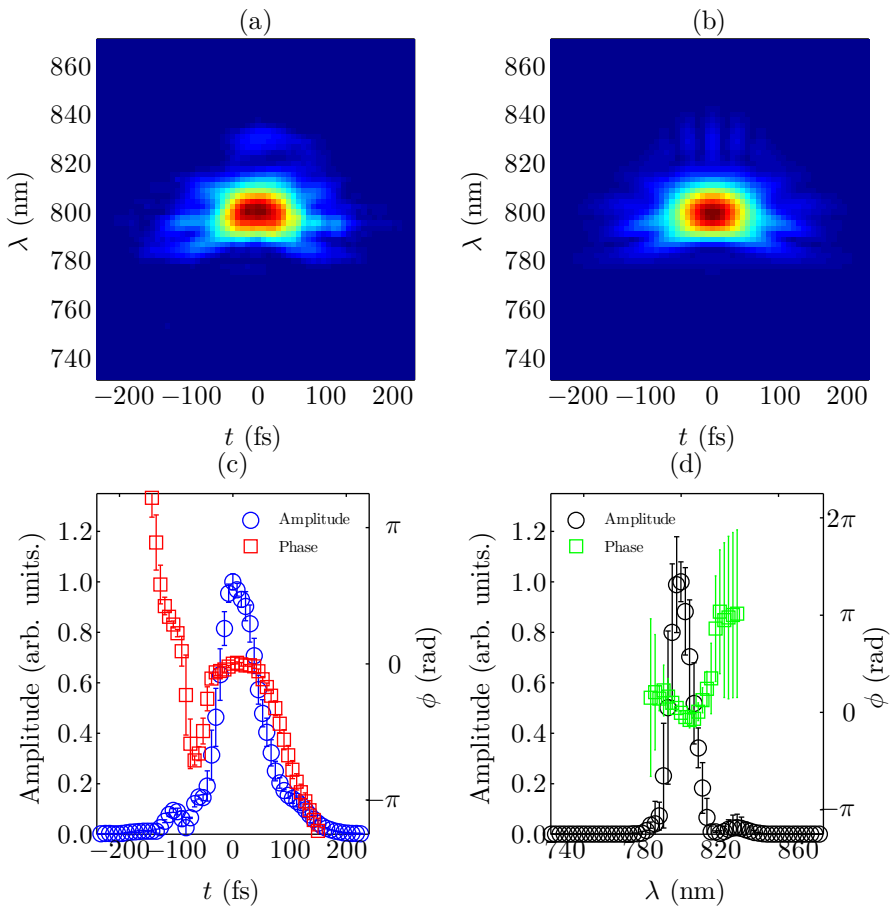

FIGURE 1. Measurement of non-Gaussian λ = 800 nm wavelength Ti:Sapphire fs laser pulse using SHG FROG. (a) Measured SHG FROG trace. (b) Fitted (retrieved) SHG FROG trace. (c) Temporal amplitude and phase profile of laser pulse. The envelope of the electric field amplitude is plotted, rather than the intensity envelope. For portions of the pulse where the amplitude is small ($|t| > 150$ fs), the error in the retrieved phase is significant. Hence, the retrieved phase is shown only where the pulse amplitude is nonzero. (d) Spectral amplitude and phase profile of laser pulse. As with (c), the retrieved phase is not shown where the amplitude is small. Uncertainties in (c, d) were determined using bootstrap statistical resampling of the measured FROG trace [21].

of a relativistic electron is $\Delta E_l = 29.3 \pm 2.0$ keV. However, if the measured phase distribution is included (Fig. 2, $A(t)\cos\phi$), the maximum energy gain for a relativistic electron is $\Delta E_l = 22.6 \pm 3.2$ keV. For a DLA experiment without pulse-front tilt, this would have significant consequences for the energy gain of electrons and the interpreted peak accelerating gradient (factor of 1.3 between the two). The assumption that the temporal phase is flat along the pulse will give the greatest electron energy gain from the pulse, subsequently yielding the lowest (conservative) limit for the estimated peak gradient. If the temporal phase varies along the pulse, segments of the pulse in time may be decelerating for a relativistic electron beam, resulting in a lower electron energy gain for a given peak accelerating gradient.

DISCUSSION

We note that in the work of Ref. [11], the structure was operated with fluences below the material damage threshold. For structures operating below the material damage limit, higher peak accelerating gradients are possible using the same laser pulse duration.

The application of FROG in DLA experiments with fs laser pulses has highlighted an important consideration: the

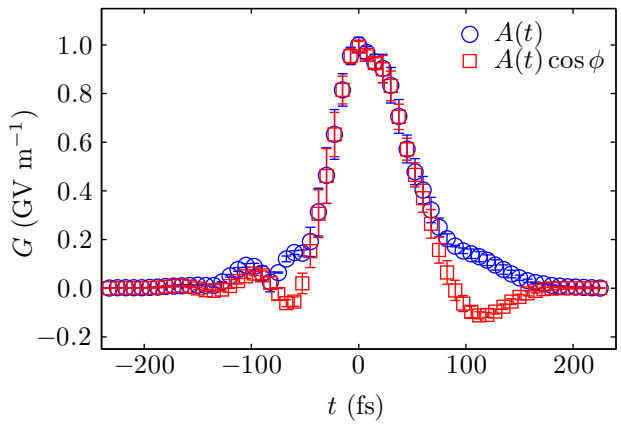

FIGURE 2. Accelerating gradient from laser pulse electric field envelope. The field envelope is plotted from the measured FROG trace [Fig. 1(c)], with the measured temporal amplitude, $A(t)$, represented by ∘, and the temporal amplitude and phase together, $A(t)\cos\phi$, represented by □. Inspection of the □ trace shows that the tails are out of phase with respect to the pulse peak, and, as such, the tails of the pulse are decelerating.

laser pulse may partially decelerate the electrons (although still with net energy gain). In the long term, however, this is unlikely to impact the maximum energy gain of an electron in a DLA. The use of laser pulses with ∼100 fs pulse durations limits the interaction length to ∼30 μm. Ideally, the DLA would be illuminated by an incoming laser with a pulse-front tilt of 45° with respect to the structure [15]. Therefore, a relativistic electron would be accelerated by the peak of the laser pulse over the length of the structure: the peak amplitude in field, with constant phase. This is one strategy planned to be pursued in future experiments, to extend the energy gain in a DLA while retaining the desirable high accelerating gradients. Such a strategy could usefully be employed to extend the interaction length to ∼1 mm. Further extension of the interaction length will additionally require periodic focusing elements to focus the electron beam [22].

The DLA structures demonstrated to date have been fabricated from fused silica and silicon. Other materials (in particular, sapphire) have been measured with single pulse damage thresholds significantly higher than these materials [23]. The use of such materials in future DLA structures could result in devices with higher accelerating gradients.

DLA experiments using relativistic electron beams are planned at several facilities in the coming years. At the PEGASUS electron linear accelerator at UCLA, DLA experiments are presently being performed using 8 MeV electrons [24]. A similar facility that could also be used for DLA experiments is the Versatile Electron Linear Accelerator (VELA) at Daresbury Laboratory [25, 26]. Future experiments with higher energy electron beams are planned at upcoming facilities. In particular, DLA experiments with 100 MeV electrons are proposed at the Short Innovative Bunches and Accelerators at DESY (SINBAD) facility [27, 28, 29], and at SwissFEL at the Paul Scherrer Institute [30].

SUMMARY

The peak accelerating gradient in DLAs has increased significantly over recent years. Principally, this has been achieved through the use of femtosecond rather than picosecond laser pulses, in combination with high damage threshold dielectric materials such as fused silica. However, evaluating the peak accelerating gradient of such pulses is complicated by non-ideal phase and amplitude distributions. In the present work, we outlined a method to determine the peak accelerating gradient in a DLA powered by femtosecond laser pulses. An example laser pulse was used to demonstrate that inclusion of phase information resulted in a factor of 1.3 difference in the evaluated peak acceleration gradient.

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