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Gradient Dependence on Electric Field

At the structure surface boundary, conservation of energy dictates that,

$$\frac{1}{2}\epsilon_0\epsilon_r E_s^2 = \frac{1}{2}\epsilon_0 E_0^2 \rightarrow E_s^2 = \frac{E_0^2}{\epsilon_r} \rightarrow E_s = \frac{E_0}{n}$$

where ϵ_0 is the vacuum permittivity, ϵ_r is the material permittivity, E_s is the field in the structure, E_0 is the incident field, and $n = \sqrt{\epsilon_r}$ is the index of refraction of the structure. Finite difference time domain (FDTD) simulations allow calculation of the fields in the structure, and therefore, a direct computation of the acceleration gradient from:

$$G = q < E_z >= \frac{q}{\lambda}\int_0^\lambda E_z(\mathbf{r},t)dz \rightarrow \frac{q}{\lambda}\int_0^\lambda E_0\cos(kz)e^{i\omega z/c}dz.$$

Making use of the calculated acceleration factor $f_A = G/|E_{max}|$, where $|E_{max}|$ is the maximum field found anywhere in the structure, and the structure field enhancement factor, $\eta = E_{max}/E_0$, we can calculate the gradient for any value of the input field as given by,

$$G = \frac{\eta f_A}{n}E_0, \tag{1}$$

where n is the index of refraction of the structure. The peak incident electric field E_0 can be calculated as $E_0 = 2\sqrt{U_0/\epsilon_0 c\tau A}$, where U_0 is the input laser pulse energy, ϵ_0 is the vacuum permittivity, c is the speed of light, τ is the laser pulse length, and A is the area of the laser beam at focus. Previous calculations from electromagnetic simulations give values of $f_A = 0.215$ and $\eta = 1.30$ for the 400 nm gap structure[28]. At an input laser pulse energy of 91.8 μJ this yields an acceleration gradient between 156 MeV/m and 233 MeV/m, depending on fabrication errors, which agrees with the measured value of 191.1 $\pm$ 5.7 MeV/m shown in Fig. 3a of the text. By comparison, the 800 nm gap structure has $f_A = 0.125$, resulting in lower gradients as shown in Extended Data Fig. 4.

Gradient Dependence on Incidence Angle

Angular misalignment of the drive laser to the grating structure has a detrimental effect on the accelerating gradient of the structure. Consider a grating structure with a periodicity of λ_p, and a drive laser (of wavelength λ) incident at an angle θ away from normal. For a speed-of- light particle traveling along the structure, the acceleration is dominated by the first space harmonic,

$$E_z = E_0(y)\cos(kz)e^{i\omega t},$$

where $\omega = ck = c(2\pi/\lambda)$ and c is the speed of light.

In the case where $\theta = 0$, an on-crest relativistic particle traveling through the grating structure (along z) will sample the crest of the laser field at each period of the structure. However, in the case where $\theta \neq 0$, the fields no longer incur a 2π phase shift over each grating period since the phase fronts of the laser pulse are no longer parallel to the electron beam trajectory. A relativistic particle now sees a phase shift of $2\pi\sin\theta$ after each period of the grating structure. The field experienced by the particle over a trajectory $z(t) = ct$ is therefore $E_z e^{ikz\sin\theta}$. The resulting gradient through N periods of the structure can be calculated from,

$$G = q < E_z >= \frac{q}{N\lambda}\int E_z e^{ikz\sin\theta}dz = \frac{q}{N\lambda}\int_0^{N\lambda} E_0\cos(kz)e^{i\omega z/c}e^{ikz\sin\theta}dz,$$

which upon integration produces

$$G = E_0\left(\frac{1+\sin\theta}{2+\sin\theta}\right)\frac{\sin(2\pi N\sin\theta)}{2\pi N\sin\theta}. \tag{2}$$

The electron beam interaction with the now spatially-modulated fields is only phase-synchronous over N periods of the structure, and this expression suggests that long accelerator sections require precise alignment for phase control. Extended Data Fig. 5b shows the gradient dependence on incidence angle in the 400 nm gap structure. A fit of the data to this expression reveals a value of N = 563 ± 104 periods over which the laser-electron interaction occurs, and an angular alignment in our experiment better than $0.02°$.

Applications to Energy Frontier Science

To reach 10 TeV center-of-mass energies, a next generation lepton collider based on traditional RF microwave technology would need to be over 100 km in length and would likely cost tens of billions of dollars to build. Due to the inverse scaling of the interaction cross section with energy, the required luminosity for such a machine would be as much as 100 times higher than proposed 1-3TeV machines (ILC and CLIC), producing a luminosity goal of order 10^{36} cm^2/s. In attempting to meet these requirements in a smaller cost/size footprint using advanced acceleration schemes, the increased beam energy spread from radiative loss during beam-beam interaction (beamstrahlung) at the interaction point becomes a pressing concern. Since the beamstrahlung parameter is proportional to bunch charge, a straightforward approach to reducing it is to use small bunch charges, with the resulting quadratic decrease in luminosity compensated by higher repetition rates. This is the natural operating regime of the DLA scheme, with the requisite average laser power ($>$100 MW) and high ($>$10 MHz) repetition rates to be provided by modern fiber lasers and microbunched beams. Microbunching of a longer beam is desired to fit the particles into individual acceleration buckets. It is a means for both improved system efficiency as well as better beam quality of the accelerated beam[23, 29].

In the present experiment, the electron bunch is many optical cycles in duration. Cherenkov wakefield radiation induced by interaction with the structure is therefore a Schottky excitation that is not coherent and produces no significant reduction in gradient. However, for a beam that is bunched in the manner described in above, this is not the case. To estimate the wake effects from short high peak-current bunches corresponding to an optimized injection scenario, electromagnetic finite element simulations were conducted of a 10 fC 100 attosecond long electron bunch traversing up to 10 periods of the structure. The corresponding loss factor for the short-range wakes was 0.12 GV/m, which is less than half the highest observed accelerating gradient in the present experiment and an order of magnitude lower than expected achievable gradients in such structures. The long range wakes appear to be of less concern in this particular structure, since its design permits the wakefield radiation to dissipate rather than return to the axis of the structure.

References

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