APPLICATIONS FOR OPTICAL-SCALE DIELECTRIC LASER ACCELERATORS

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Abstract

Particle acceleration in dielectric laser-driven microstructures, recently demonstrated at SLAC, holds the promise of providing low-cost compact accelerators for a wide variety of uses. Laser-driven undulators based upon this concept could attain very short (mm to sub-mm) periods with multi-Tesla field strengths. And since dielectric laser accelerators operate optimally with optical-scale electron bunch formats, radiation production with high repetition rate (10s of MHz) attosecond-scale pulses is a natural combination. We present preliminary analysis of the harmonic field structure for a periodic undulator based on this concept.

INTRODUCTION

The increasingly prohibitive cost and size of modern accelerator facilities has prompted interest in a variety of schemes for accelerating particles at higher gradients than traditional metallic cavity accelerators can provide, rapid fabrication techniques, and more readily available energy sources. One of the most promising of these schemes is the use of dielectric near-field structures powered by an infrared (IR) laser to produce a confined accelerating mode. Since the size of the confining beam channel scales with the wavelength of the source, the apertures of such structures are at most a few microns in transverse size. As a result, particle beam confinement requires a new operating regime with beams of low charge (10-100 fC) and ultra-low normalized emittance (1-10 nm). The bunches should ideally be short compared to the optical wavelength (10-100 fs), must be spaced at the optical period of the laser (or an integer multiple thereof), and should come in bunch trains commensurate with typical solid state laser pulse lengths (10 fs - 1 ps). The decrease in luminosity due to such small bunch charges are compensated by the fact that solid state lasers permit repetition rates 3 orders of magnitude higher than typical microwave sources. The requisite dielectric structures can be fabricated with nanometer-level precision on silicon wafers using modern solid state fabrication methods, and the first experimental demonstration of high-gradient acceleration in such structures has been recently reported [1].

The DLA concept leverages well-established industrial fabrication capabilities and the commercial availability of tabletop lasers to reduce cost, while offering significantly higher accelerating gradients, and therefore a smaller footprint. Power estimates for the DLA scenario are comparable with convention RF technology, assuming that similar power efficiency (near 100%) for guided wave systems can be achieved, 40% wall plug laser efficiencies (feasible with solid state Thulium fiber laser systems), and 40% laser to electron beam coupling (consistent with published calculations).

This research has significant near and long-term applications for energy frontier science [2, 3]. Additional applications including radiation production for compact medical x-ray sources, university-scale free electron lasers, NMR security scanners, and food sterilization are beginning to be explored. A dielectric laser-driven deflector, operating on the same basic principles as recently demonstrated accelerator devices, was proposed by Plettner and Byer [4]. The scheme uses a pair of dielectric gratings excited transversely by a laser beam and separated by a gap of order the laser wavelength where a beam of electrons would travel. By changing the sign of the excitation between successive structures (e.g. by alternating the direction of illumination) an optically powered undulator could be constructed to create laser driven micro-undulators for production of attosecond-scale radiation pulses synchronized with the electron bunch.

As a next step in exploring this concept in more detail, the commercial electromagnetic finite element code HFSS 12.0 was used to obtain realistic field profiles along the axis of an electron beam propagating in a single stage of deflection (representing half of one undulator period). These fields are analyzed with respect to the injection phase of a test electron and the deflecting forces calculated to produce a single-period model of the proposed undulator concept.

BACKGROUND

The deflector design proposed in Ref. [4] consists of a pair of coplanar gratings with a pillar height g separated by a gap of width w. If the gratings are constructed of an optically transmissive material (such as glass) an electromagnetic mode can be excited in the gap region by transverse illumination of the structure with a monochromatic plane wave. The resultant confined mode is found to produce a net deflecting force transverse on a trajectory lying in the midplane between the two gratings at an angle $\pi - \alpha$ relative to the direction of the grating lines. Consquently

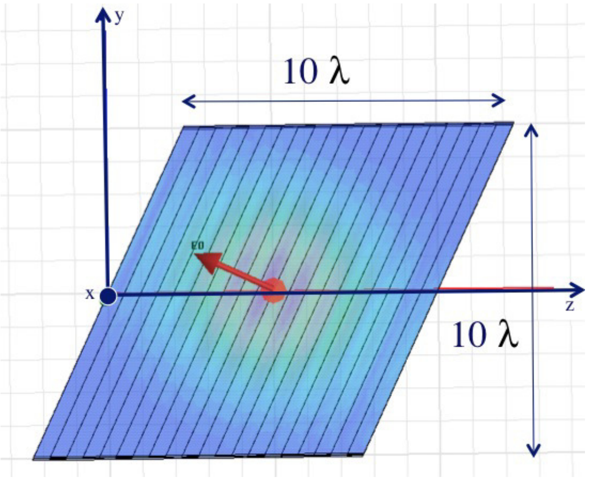

Figure 1: HFSS simulation geometry with superimposed color contour plot of the Gaussian excitation.

by tilting the gratings at an angle α relative to the beam axis in the plane parallel to the grating surfaces a net transverse deflecting force can be imposed on a charged particle traveling between the gratings. The maximum amplitude of this deflection is found to be $F_\perp \approx qE_0 sin^2\alpha$, where E_0 is the electric field amplitude of the incident laser field and q is the particle charge, which occurs for the optimized geometrical values $w = 0.4\lambda$, $\alpha = 25°$, and $g = 0.85\lambda$. For a silicon dioxide structure with a 0.3 ps laser pulse, the corresponding peak surface electric field corresponding to the damage limit is $E_{pk} \approx 8.2$ GV/m, and the corresponding incident laser field is $E_0 = E_{pk}/3$, corresponding to an equivalent undulator magnetic deflection field $B_u = \mu_0 E_0/Z_0$ = 1.6 T.

It should be noted that the deflection has both x and y components and that there is also a significant z component of net accelerating force. To create an undulator from such structures, they can be staged, with successive stages of deflection illuminated from opposite sides so as to alternate the sign of the deflection force. Since the longitudinal extent of the deflecting force in each stage is determined by the transverse extent of the exciting laser field, in principle the period of such an undulator could be many times the laser wavelength.

SIMULATIONS

A single stage of the proposed deflector (half a period of the undulator) was simulated using the commercial electromagnetic finite element code HFSS 12.0. The computational volume includes the entire structure, with no symmetry planes, and absorbing boundary conditions on all exterior boundaries. The geometry is shown in Fig. 1. The model is excited by a Gaussian laser mode at normal incidence propagating in the negative x direction transverse to the planes of the gratings. The beam axis is taken to be the positive z direction, and the primary deflection component is in the x direction.

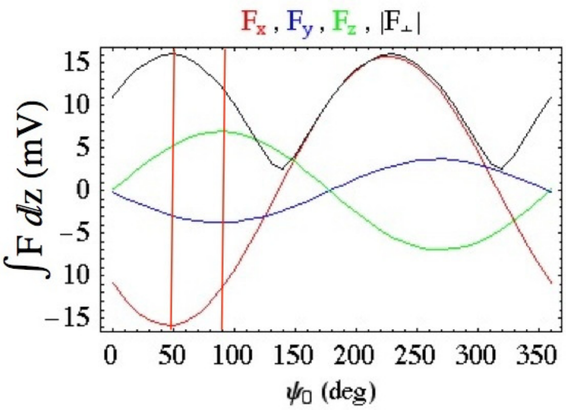

Figure 2: Computed force components as a function of particle injection phase, for an incident field E_0 = 1 V/m, integrated over half an undulator period (10λ).

For the structure orientation and dimentions, we take the optimized values $\alpha = 25°$, $w = 0.4\lambda$, $g = 0.85\lambda$ as calculated in Ref. [4], with the excitation field polarized perpendicular to the lines of the gratings. The fields are then extracted along the z-axis and the integrated force on a speed of light particle is computed. The force components as a function of injection phase ψ_0 of the particle, for an incident laser field with an electric field amplitude $E_0 = 1$ V/m, are shown in Fig. 2. We see that the deflecting force $F_\perp$ is dominated by the x component. At $\psi_0 = 0$, the integrated force on the particle is entirely in the x direction, as the contributions from the other two components are zero. If the fields from the half-period are mirrored in z to produce a single undulator period, the results can be harmonically analyzed by a Fourier sine decomposition as

$$F_x(z) = \frac{a_0}{2}\sum_{n=1}^{\infty}[a_n \cos(n\pi x/L) + b_n \sin(n\pi x/L)] \quad (1)$$

The resulting harmonics at $\psi_0 = 0$ are found to have a mixture of harmonic contributions from both the cosine and sine terms. However, at an injection phase of 90°, $a_n = 0$, the accelerating (z) contribution is a maximum but the field harmonics are sinusoidal with dominant contributions at the first and third harmonics ($b_1 = 0.2E_0$, $b_3 = 0.05E_0$). The corresponding lowest-order deflection force is consistent with the analytical predictions of the prior section. The next significant harmonic contributions appear at $n = 18$ and higher, and correspond to the fast oscillation component related to the laser wavelength λ, as seen in the right-hand plot of Fig. 3. The first and third harmonic sinusoids are combined to produce the red curve superimposed upon the plot in Fig. 3. If the system is scaled to larger undulator periods (of order 100 λ), these components get pushed to higher n values and hence the undulator parameter contributions K_n from these higher harmonics become increasingly ignorable.

The significant third harmonic contribution, however, will contribute significantly to the radiation produced if

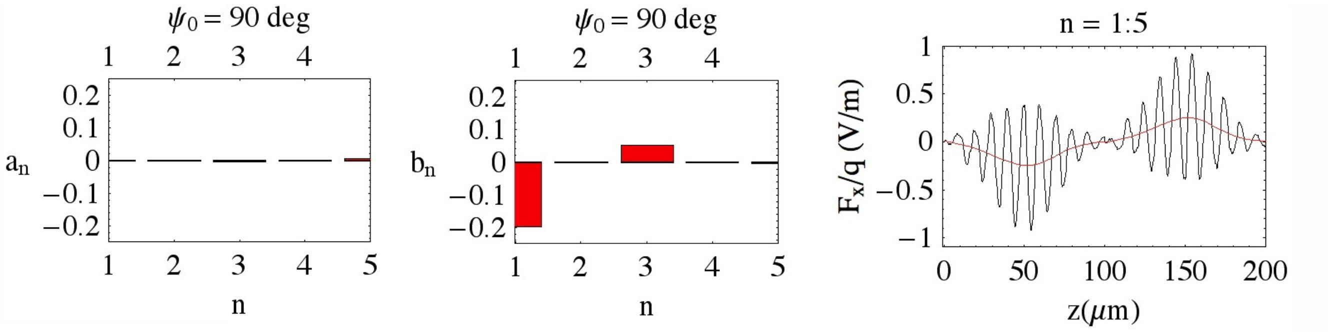

Figure 3: Harmonic analysis of a single undulator period for 90° injection phase, showing the cosine and sine harmonic terms and the dominant x force component (black curve) with superposition of the first 5 harmonics (red curve).

this device is used as an undulator for an optical-scale free electron laser. In traditional undulator designs, third harmonic field content occurs as a perturbative contribution due to the nonlinear motion of the electrons in the undulator field. However, the presence of significant inherent third harmonic has recently been studied as a mechanism to intentionally generate efficient third harmonics of the fundamental FEL radiation [5]. In addition, although we have here assumed a Gaussian laser mode for simplicity, the harmonics of the undulator fields may be manipulated (and the third harmonic contribution enhanced or reduced) by transverse shaping of the incident laser mode profile.

Unlike other electromagnetic undulator concepts, the undulator period in this scheme is set by the length of each deflection stage and can therefore be much larger than the driving wavelength. From simple 1D calculations, undulators based upon this concept could attain very short (mm to sub-mm) periods with multi-Tesla field strengths: an undulator with a 250 μm period driven by a 2 μm solid state laser would have a gain length of 4 cm and an X-ray photon energy of 10 keV when driven by a 500 MeV electron beam. Since DLA structures operate optimally with optical-scale electron bunch formats, high repetition rate (10s of MHz) attosecond-scale pulses are a natural combination.

CONCLUSIONS

The grating-based optical deflector concept presented previously by Pletter and Byer presents the possibility of creating a FEL undulator compatible with future laser-driven accelerators. We have simulated one period of such an undulator concept using an electromagnetic finite element code with a grating excited transversely by a Gaussian monochromatic mode. The axial fields extracted do show a significant integrated transverse deflecting force, as well as a net integrated acceleration, as predicted. However, while in Ref. [4], the ratio of these components is predicted to be $F_z/F_\perp \approx 2$, we find that the accelerating component is generally smaller than the deflecting force, and varies significantly with injection phase, an effect not previously noted. In addition, we find that for a Gaussian laser mode, the fields contain significant third harmonic content. The impact of these observations will be explored in future by analytical calculations as well as computational analysis using FEL codes. Prototype devices based on a modified version of the architecture reported in [1] are being developed for experimental testing at SLAC.

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