PROPOSED TABLETOP LASER-DRIVEN COHERENT X-RAY SOURCE*

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Abstract

We describe the concept of an all-dielectric laser-driven undulator for the generation of coherent X-rays. The proposed laser-driven undulator is expected to produce internal deflection forces equivalent to a several-Tesla magnetic field acting on a speed-of-light particle. The key idea for this laser-driven undulator is its ability to provide phase synchronicity between the deflection force and the electron beam for a distance that is much greater than the laser wavelength. A possible conceptual tabletop SASE-FEL device composed by such an integrated laser-driven accelerator-undulator system is explored.

INTRODUCTION

One of the potential main traits from future structure loaded laser-driven particle accelerators is their promise for attosecond electron bunches and for higher gradients than RF particle accelerators. Therefore the possibility for employing such an accelerator as a compact electron source for a SASE-FEL device is interesting to explore. A meter long laser accelerator could deliver an optically bunched GeV energy electron beam into an undulator, and to preserve an all-tabletop system a matching compact undulator is highly desirable. To this end we propose a dielectric based laser-deflection structure that is MEMs based.

THE UNDULATOR

The key aspect of the proposed laser-driven undulator is the maintenance of phase synchronicity between the electromagnetic field and the travelling particle, which is designed to extend this condition for a distance that is much larger than the wavelength of the driving electromagnetic wave. Such a condition decouples the laser wavelength from the undulator period and hence allows for use of near-infrared, high peak power laser beams that drive undulators with arbitrarily long periods. To attain extended phase synchronicity we explore the concept of introducing a periodic phase modulation of the electromagnetic wave near the particle trajectory. Particle accelerators that employ this principle have been proposed in the past [1,2]. Here we apply the concept of phase-synchronous particle deflection and explore a structure geometry with some resemblance to [2] that is designed for laser-driven particle deflection.

A perspective view of a section of the proposed deflection structure is illustrated in Figure 1. The periodic grooves of the vacuum channel are oriented at an angle α with respect to the electron beam trajectory. These grooves introduce a phase modulation of the electromagnetic field in the vacuum channel that is responsible for the extended phase synchronicity condition with the electron beam. The period of the vacuum channel grooves, denoted by λ_p in Figure 1, is chosen such that its projection on the electron beam axis equals the laser wavelength λ, such that $\lambda_p = \lambda\cos\alpha$. In the structure coordinates the particle velocity vector is given by $\vec{v}(t) = c(\hat{y}\cos\alpha + \hat{z}\sin\alpha)$. The laser beam is a plane wave with the phase front at normal incidence the structure, travelling in the $\hat{x}$ - direction.

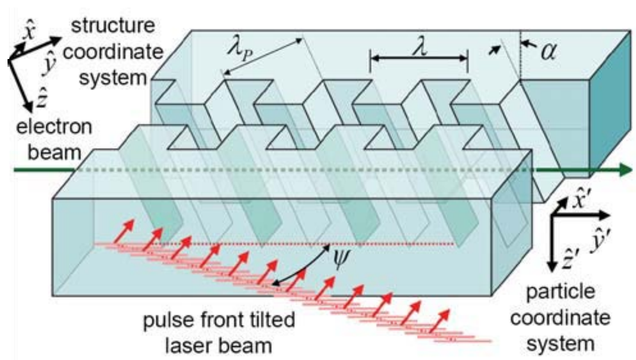

Figure 1: Perspective view of the deflection structure.

A configuration of this type, where the periodic structure is oriented at an angle to the electron beam, satisfies the phase synchronicity condition for a non-zero deflection force acting on a speed-of-light particle [3]. To understand this finding consider the special case where the input laser field is monochromatic and is polarized along the y-axis. Diffraction in the vacuum channel produces two E_x and E_y electric field components and a magnetic field component B_z. The Lorentz force from this electro-magnetic field on the particle is

$$\vec{F} = \mathrm{Re}\left[q(E_x + cB_z\cos\alpha)\hat{x} + qE_y\hat{y}\right] \quad (1)$$

The average deflection force experienced by the moving particle is therefore

$$\left\langle \vec{F} \right\rangle = \lim_{L\to\infty}\frac{1}{L}\int_{-S/2}^{S/2}\vec{F}(\vec{r}(t))\cdot\vec{v}\,dt \quad (2)$$

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Due to the periodic structure the field components are also periodic [4] . Thus E_x, E_y and B_z can be expressed as Fourier expansions of the form

$$E_x(0,y,t)=\sum_{n=-\infty}^{+\infty}U_n e^{ik_p ny}e^{ikct}$$
$$E_y(0,y,t)=\sum_{n=-\infty}^{+\infty}V_n e^{ik_p ny}e^{ikct} \quad (3)$$
$$B_z(0,y,t)=\sum_{n=-\infty}^{+\infty}W_n e^{ik_p ny}e^{ikct}$$

In the vacuum these time harmonic fields are related by $cd_yB_z=ikE_x$. This establishes the relation between the Fourier coefficients of equation 3 that satisfy $cW_n=(k/nk_p)U_n$. Hence the average deflection force takes the form

$$\langle F_x\rangle = q\,\mathrm{Re}\left(e^{-iky_0}\sum_{n=-\infty}^{+\infty}\left[\left\{1+\frac{k\cos\alpha}{nk_p}\right\}U_n \times\lim_{L\to\infty}\left(\frac{1}{L}\int_0^L e^{i(k_pn+k/\cos\alpha)y}dy\right)\right]\right) \quad (4)$$
$$\langle F_y\rangle = q\,\mathrm{Re}\left(e^{-iky_0}\sum_{n=-\infty}^{+\infty}V_n\lim_{L\to\infty}\left(\frac{1}{L}\int_0^L e^{i(k_pn+k/\cos\alpha)y(y')}dy'\right)\right)$$

The extended phase synchronicity is satisfied for the coefficient for which the oscillatory term in the path-integral is constant; $k_pn+k/\cos\alpha=0$. For the lowest order component, $n=1$, $k_p=k\cos\alpha$. Thus the average acceleration and deflection force components as seen in the structure coordinate system are $\langle F_y\rangle=q\,\mathrm{Re}(e^{-iky_0}V_{-1})$, $\langle F_x\rangle=q\,\mathrm{Re}(e^{-iky_0}U_{-1})\sin^2\alpha$, and $\langle F_z\rangle=0$. In the electron beam coordinate system the average force components are

$$\langle F_{\perp,x'}\rangle = q\,\mathrm{Re}(e^{-iky_0}U_{-1})\sin^2\alpha$$
$$\langle F_{\parallel,y'}\rangle = q\,\mathrm{Re}(+e^{-iky_0}V_{-1})\cos\alpha \quad (5)$$
$$\langle F_{\perp,z'}\rangle = q\,\mathrm{Re}(-e^{-iky_0}V_{-1})\sin\alpha$$

From equation 4 it can be seen that the nonzero synchronous deflection force components can only exist when $\alpha\neq0$. Operation with an ultra-short laser implies a wide range of laser wavelengths. It can be shown that each individual wavelength can satisfy the phase-synchronicity condition when its phase-front is tilted at an angle $\Delta\varphi$ that that is proportional to the offset from the center frequency

$$\frac{1}{\cos\alpha}=k\frac{\Delta\varphi}{\Delta k}\equiv\tan\psi \quad (6)$$

Equation 6 describes a pulse front tilted laser wave having a pulse front tilt angle ψ that is related to the groove tilt angle by $\tan\psi=\csc\alpha$ [5].

Figure 2a shows the cross-section of a quartz structure powered by an input laser plane wave of amplitude $E_{laser}=1$. The groove tilt angle for this example is assumed to be $\alpha=30°$. Two laser polarizations are possible: TM waves, having the input electric field orthogonal to the groove channels, and TE waves, with heir electric field parallel to the groove channels. As shown in figure 2b and 2c, both polarizations generate a deflection gradient $\langle G_i\rangle=\langle F_i/q\rangle$ that is a significant fraction of the input laser field amplitude.

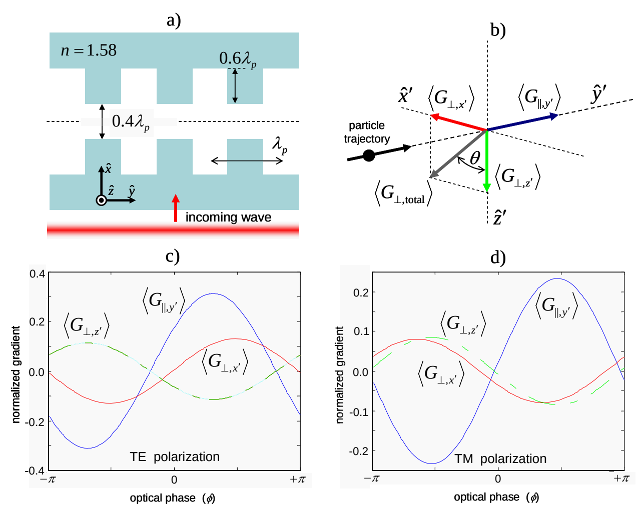

Figure 2

The deflection strength of the undulator

FDTD simulations show that for this structure the peak electric field is located at the center region of the pillar surface and is about twice the input laser amplitude; $|E_{\max}|\sim2|E_{laser}|$. $E_{\max}$ sets the maximum laser fluence applicable to the structure, and for ultra-short near-IR laser beams it is not to exceed 1 J/cm^2 [6]. For a 10 fsec pulse this corresponds to $E_{\max}\sim25\,\mathrm{GV/m}$. As shown in figure 2c $\langle G_{\perp,TE}\rangle\sim0.14\,E_{laser}$, which leads to an average deflection gradient from the TE polarized laser beam of $\langle G_{\perp,TE}\rangle\sim2\,\mathrm{GV/m}$. For a speed-of-light particle such a deflection gradient corresponds to a ~6T magnetic deflection field. Hence a structure of this kind provides an ideal means for beam steering in a future MEMs based particle accelerator. A laser-driven undulator would be a natural extension of this deflection structure, where the phase of the laser beam is reversed every M_u structure periods, generating an effective undulator period of $\lambda_u = 2M_u\lambda$. The unique characteristic of this proposed laser-driven undulator is its ability to provide phase synchronicity between the deflection force and the electron beam for a distance that is much greater than the laser wavelength. Since the undulator period is determined by the MEMs design, it is flexible and can be readily scaled to sub-mm periods. Finally, the structure is dielectric and its shape closely resembles other proposed laser accelerator structures, which could potentially allow for an all-dielectric MEMs based accelerator-undulator system of very compact dimensions. An undulator with a ~3T deflection strength and a period of ½ mm would have an undulator parameter of *K*~0.2.

A POSSIBLE RADIATION SOURCE EXAMPLE

The realization of an integrated all-laser-driven particle accelerator still lies in the future and therefore precise electron beam parameters from such a device are speculative. Still, theoretical work has yielded a set of plausible parameters and hence the concept of a dielectric structure laser-driven accelerator followed by a laser-driven undulator for SASE-FEL generation is interesting to explore.

Dielectric structure laser-driven particle accelerators are expected to deliver acceleration gradients of ~1 GeV/m, therefore a few-meter long laser accelerator could provide a GeV energy electron beam into the laser-driven undulator. The optical bunching at near-infrared wavelengths from the laser field is expected to generate a few-attosecond electron pulse structure. The transverse invariant emittance supported by structure based laser-particle accelerators has been estimated to be capable of reaching emittance values on the order of 10^{-9} m-rad or lower [1,7]. Depending on the specific architecture of the accelerator structure in question beam loading considerations estimate optimum bunch charge values ranging from 1fC to a pC. Table 1 lists the assumed electron beam and undulator parameters for the example of the conceptual laser-driven SASE-FEL illustrated here.

Table 1:Assumed electron beam and undulator parameters

Beam energy	2 GeV
Transverse emittance	10^{-9} m-rad [1,7]
Energy spread	0.5%
Bunch duration	5 attosec
Bunch charge	1 pC [2]
Spot size	180 nm
Undulator period	½ mm
Undulator parameter	*K*~0.2
FEL photon energy	~70 keV

Figure 3 shows the expected growth of the X-ray pulse when modelled with GENESIS. Saturation is expected to occur within several cm of undulator structure, and due to the short length of the undulator the temporal structure of the X-ray pulse is expected to preserve the few-attosecond pulse duration.

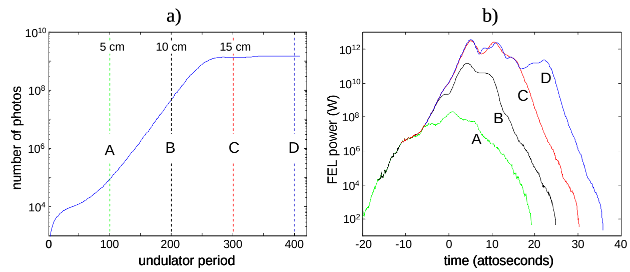

Figure 3

This simple first-cut simulation based on the parameters of table 1 illustrates our envisioned concept of a possible sub-meter MEMs based dielectric undulator and its potential for generation of ultra-short SASE-FEL pulses. To summarize, the key characteristics of the proposed dielectric undulator structure include its ability to provide extended phase synchronicity of the laser deflection force with the electron beam and its compatibility with ultra-short near-IR laser wavelengths.

Our future work on this concept will include a more detailed modelling of the possible FEL growth and of beam transport issues in both the accelerator and undulator. In addition, in the near future we plan to carry out as set of simple experimental tests of the dielectric laser deflector structure with the 60 MeV electron beam available at the E163 experiment at SLAC. We thank Northrop Grumman their support and participation in this research effort.

REFERENCES

[1] J. Rosenzweig, A. Murokh, C. Pellegrini, "A proposed dielectric-loaded resonant laser accelerator", Phys. Rev. Lett. 74, 002467 (1995)
[2] T. Plettner, P.P. Lu, R.L. Byer, "Proposed few-optical cycle laser–driven particle accelerator structure", Phys. Rev. ST AB 9, 111301 (2006)
[3] T. Plettner, "Phase synchronicity conditions from pulse-front tilted laser beams in periodic structures", SLAC-PUB-12458 (2007)
[4] M. Nevière, E. Popov, "Light Propagation in Periodic media", Marcel Decker, Inc. p. 21-22 (2003)
[5] J. Hebling, "Derivation of the pulse front tilt caused be angular dispersion", Optical and Quantum Electronics 28 1759-1763 (1996)
[6] B. C. Stuart et al, "Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses", Physical Review Letters 74, 2248 (1995)
[7] B. Cowan, "Photonic Crystal Laser-Driven Accelerator Structures" PhD thesis, ch 3.5 particle beam dynamics (2007)

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