Nuclear Instruments and Methods in Physics Research A 593 (2008) 63–66

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Microstructure-based laser-driven free-electron laser

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ARTICLE INFO

Available online 10 May 2008

*Keywords:*
Dielectric-structure undulator
Laser-driven particle acceleration
Phase-synchronous deflection
Few-attosecond time structure

ABSTRACT

We propose an all-dielectric laser-driven undulator. This undulator consists of laser-driven deflection structures where the deflection force from the laser is phase-synchronous with the electron beam. This allows for an undulator period that is much greater than the laser wavelength. Due to the possibility of high peak electric fields from ultra-short pulse lasers on dielectric materials, the proposed undulator is expected to produce phase-synchronous GV/m deflection fields on a relativistic electron bunch and therefore lead to a very compact free-electron-based radiation device.

## 1. Introduction

The dielectric-structure undulator proposed here is envisioned for application with future structure-loaded laser-driven particle accelerators. These accelerators are expected to operate in a similar fashion to RF accelerators, but with their dimensions and the drive wavelength scaled down by four orders of magnitude. Due to the femtosecond optical cycle duration of the driving laser beam the electron bunch duration from these accelerators is expected to lie in the attosecond regime. Furthermore, the predicted ~1 GeV/m gradient from these accelerators [1] potentially allows for a meter-length GeV electron source. Finally, due to their miniature dimensions these structures support emittance values of $10^{-9}$ mrad [2], but at the same time it can only carry bunch charges in the fC range [3]. For an all-tabletop system that is based on this accelerator, a matching compact undulator is highly desirable. To this end, we propose a dielectric-based laser-deflection structure that is MEMs based and that can serve as an undulator segment. Table 1 lists a set of expected electron beam parameters that could be delivered by a meter-scale structure-based laser accelerator into an undulator.

## 2. The undulator

The proposed undulator relies on laser fields applied to a near-field dielectric structure to provide a deflection force. Active-field undulators are not a new concept; intense free-space laser beam wigglers [4] and microwave-cavity undulators [5] have been investigated in the past.

The main difference between the proposed dielectric-structure undulator to the other active-field concepts is that the deflection force delivered from the laser beam inside the structure is phase synchronous with the electron beam. This allows the undulator period to be independent and much longer than the wavelength of the driving laser. The laser-deflection segments of the proposed undulator function in a similar fashion to the structure-based particle accelerators.

The deflection force depends on both the transverse electric and the magnetic field components acting on the particle, and these are set by the specific design of the dielectric structure. Periodic phase modulation of the electromagnetic wave near the particle trajectory is one possible means for providing phase synchronicity of the field with the electron beam. Particle accelerators that employ this principle have been proposed in the past [6,7]. A possible periodic structure that supports a phase-synchronous deflection force is shown in Fig. 1. The grooves of the vacuum channel are oriented at an angle $\alpha$ with respect to the electron beam trajectory. The period of the vacuum channel grooves, denoted by $\lambda_p$ in Fig. 1, is chosen such that its projection on the electron beam axis equals the laser wavelength $\lambda$, such that $\lambda_p = \lambda\cos\alpha$. The oblique orientation of the grooves with respect to the electron beam is responsible for the synchronous deflection force.

Consider a laser plane wave incident on the structure shown in Fig. 1 with the electric field orthogonal and the magnetic field parallel to the grooves, labeled as TE polarization. Assume the laser plane wave is incident, as shown in Fig. 1b. A detailed analysis for the pulse-front tilted wave incident on such a structure has been carried out elsewhere [8]. A simplified analysis employing a monochromatic plane wave is presented here. For such an incident wave, the electromagnetic field components inside the vacuum are periodic and can be represented as a Fourier expansion [9]

$$E_x(0,y,t) = \sum_{n=-\infty}^{+\infty} U_n e^{ik_p ny} e^{ikct}$$

$$E_y(0,y,t) = \sum_{n=-\infty}^{+\infty} V_n e^{ik_p ny} e^{ikct}$$

$$B_z(0,y,t) = \sum_{n=-\infty}^{+\infty} W_n e^{ik_p ny} e^{ikct}$$

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doi:10.1016/j.nima.2008.04.063

**Table 1**
Possible beam parameters from a structure-based laser-driven particle accelerator

| Parameter | Value |
|---|---|
| Energy | 2 GeV |
| Energy spread | $10^{-3}$ |
| Normalized emittance | $10^{-9}$ m |
| Bunch charge | 20 fC |
| Bunch duration | 5 attos |
| Beam transverse dimension | 200 nm |

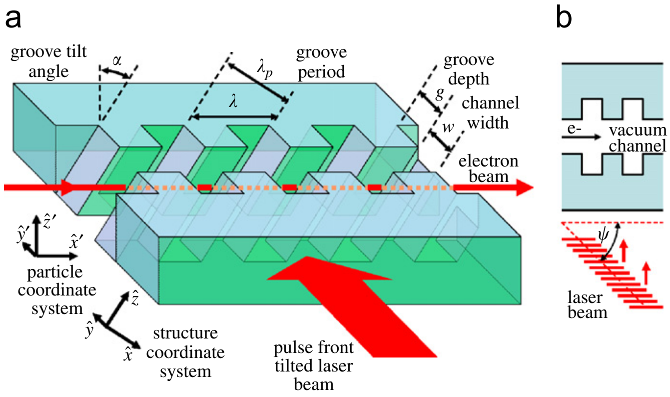

**Fig. 1.** (a) Perspective view of a section of the deflection structure. (b) The corresponding top view. The pulse-front tilted laser beam is at normal incidence to the vacuum channel.

where the individual coefficients $U_n$, $V_n$ and $W_n$ are related to each other by Maxwell's equations. In the electron beam coordinate system, the average force components are

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

The nonzero synchronous deflection force components can only exist when $\alpha\neq 0$. Finite time domain simulations reveal the value of the electromagnetic field components inside the vacuum.

As an example, assume a quartz structure with an index of reflection $n = 1.58$ with a vacuum channel gap of $0.4\lambda$, a groove depth of $0.6\lambda$, and a groove tilt angle with respect to the electron beam axis of $\alpha = 20^\circ$. Evaluation with the incident TE laser wave reveals that the average phase-synchronous deflection gradient is ~7% of the local maximum electric field on the structure, which sets the maximum laser fluence applicable to the structure. For dielectric material exposed to ultra-short near-IR laser beams the fluence is not to exceed 1 J/cm$^2$ [10]. There are several near-infrared technologies for compact lasers capable of sub-100 fs pulses, such as Ti:sapphire with $\tau_{\mathrm{laser}}<8$ fs or Yb:glass with $\tau_{\mathrm{laser}}<36$ fs [11]. The maximum applicable peak electric field from a 10 fs laser pulse with the given damage threshold is approximately 25 GV/m, which leads to a maximum average deflection gradient of 2 GeV/m.

In addition to the phase-synchronous deflection force, there is a significant phase-synchronous accelerating force that in this example corresponds to 4 GeV/m. At first sight, this may seem an undesirable feature for a deflection element, and one may be inclined to provide a second laser beam with the correct optical phase from the other side of the structure to cancel out the acceleration component. However, the radiative loss factor from the very narrow-aperture structure and the small transverse beam size, which is estimated at ~100 GeV/pC/m, introduces an effective deceleration gradient on the electron bunch. In addition, there is a broadband Cherenkov wake with a loss factor of comparable magnitude [12]. Therefore, with a total loss factor near 200 GeV/m/pC, the expected unloaded 4 GeV/m acceleration gradient would be loaded to zero with a bunch charge of 20 fC, which shall be considered the upper charge limit estimate for this particular structure with an electron beam focused to a round 0.2 μm diameter. Fig. 2 shows a diagram of the proposed undulator. Individual sections of the proposed laser-deflection structure with $M_u$ grating periods may form an undulator if the sign of the deflection force from the laser is alternated between the individual sections, resulting in an undulator period that corresponds to two such structure sections.

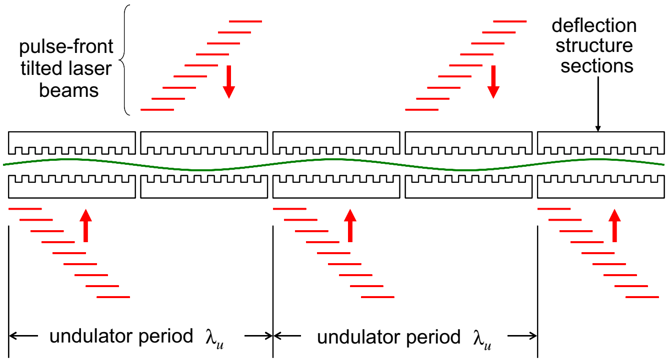

**Fig. 2.** The envisioned dielectric-structure undulator.

## 3. FEL operation of the dielectric undulator

To explore the possibility of FEL operation from the proposed structure, assume a 20 fC bunch, and for simplicity consider an undulator design with no periodic focusing elements. The length of such an undulator will be limited by the depth of focus of the electron beam ($\beta^*$). For a beam with the parameters of Table 1, the parameter $\beta^*$ corresponds to ~4 cm.

Next, the undulator period for which the operation is possible with the proposed undulator has to be determined. To this end the one-dimensional FEL model can serve as a first guide. Firstly, the normalized emittance has to follow $\varepsilon<\lambda_r/4\pi\gamma$, and secondly, the FEL gain length has to be shorter than the Rayleigh range, namely, $L_{G0}<L_R$. The two conditions establish that for an electron beam with the parameters of Table 1 the undulator period has to lie at 0.5 mm $>\lambda_u>$0.01 mm.

As an example, assume an undulator period of $\lambda_u = 0.3$ mm. For this undulator period and beam parameters of Table 1, the FEL parameter based on the one-dimensional steady-state model is $\rho\sim 6\times 10^{-3}$, the one-dimensional steady-stage gain length is $L_{G0}\sim 6$ mm or 20 undulator periods, and the corresponding Rayleigh range is four times as long. In light of the third FEL condition $\Delta\gamma/\gamma<\rho$, assume an initial energy spread of $\Delta\gamma/\gamma = 1\times 10^{-3}$. Due to the proposed short bunch length slippage can be expected to determine the FEL evolution dynamics. The five attosecond electron bunch corresponds to a longitudinal dimension of $\sigma_b = 136\lambda_r$ and the cooperation length is $L_c = 21\lambda_r$. The ratio $\sigma_b/L_c$ determines the FEL operation regime [13] and here $\sigma_b/L_c\sim 6$, which predicts a single-spike FEL output. In this regime, slippage degrades the effective gain length by $L_G = L_{G0}(1+N_s\lambda_r/3\sigma_b)$ [14]. In this example, the effective gain length becomes $L_G\sim 2.1L_{G0}$.

With the transverse beam parameters chosen to lie within the limits of the one-dimensional FEL model, a numerical model that only includes the longitudinal dimension of the electron and

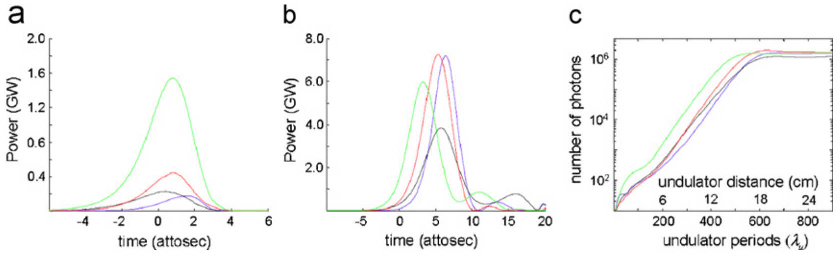

**Fig. 3.** (a) Expected FEL traces after 12 cm drift inside the undulator, (b) after 27 cm of drift, (c) corresponding total number of photons as a function of undulator length. Saturation is predicted to be reached within 18 cm of the undulator structure.

photon beam evolution allows for a first-cut estimate of the expected FEL performance of the proposed undulator. Due to the low bunch charge, the longitudinal orbit of each electron can be tracked without the need for marcoparticles with the standard FEL pendulum equations. The FEL field is tracked with the slowly varying envelope approximation. The evolution of the particles and the field envelope was stepped in time increments of one undulator period. A simple MATLAB script was written to this end. Fig. 3 illustrates the expected FEL pulse evolution from four different input electron bunches with the parameters of Table 1. Each bunch is represented with a different trace color. Fig. 3a shows the expected FEL pulses after 200 undulator periods or 12 cm of drift in the undulator. This distance corresponds to the region of exponential gain, as seen in Fig. 3c. Due to the shortness of the undulator at that point there is no significant pulse timing jitter, but a very large amplitude fluctuation. Fig. 3b shows the corresponding FEL traces after 27 cm of the undulator, corresponding to the region of superradiance. Here the power fluctuations are small, but there is significant timing jitter on the order of one pulse duration. The expected FEL pulse duration is of about 5 attos and the total number of photons is $\sim 10^6$ per pulse. With a photon energy of 100 keV, this corresponds to 200 nJ/pulse and to an effective FEL parameter of $\rho_{\mathrm{eff}} \sim 5 \times 10^{-3}$. Notice that the slope of the power gain shown in Fig. 3c in the exponential regime shows an effective gain length of ~40 undulator periods, which is in agreement with the expected lengthening of $L_G$ due to slippage.

In the described quartz-based $\lambda_u = 0.3$ mm undulator example, the vacuum channel gap is twice as wide as the electron beam focus, therefore if no focusing is provided, clipping of the electron beam from the undulator walls starts to occur with an undulator length of $L \sim 4\beta^*$, or 530 undulator periods. Therefore, in the absence of focusing, an undulator length of ~400 periods and a corresponding flux of $\sim 10^5$ photons/pulse is realistically possible. Still, with a possible 1 MHz repetition rate for a moderately amplified modelocked laser system, an average of $\sim 10^{10}$ photons/s could be expected from this system.

The expected FEL wavelength for this example lies at about 0.1 Å, which corresponds to a photon energy of 100 keV. Note that due to the short bunch duration, the bandwidth of the FEL pulse is relatively wide. Assuming a transform-limited pulse, the bandwidth is ~10%. Although the photon energy is very high, the quantum FEL parameter is ~83, and therefore the proposed set of parameters is expected to lie in the classical FEL regime [15].

Table 2 summarizes the FEL parameters expected from the proposed undulator with an electron beam having the parameters of Table 1.

**Table 2**
Proposed undulator and expected FEL beam parameters

| Parameter | Value |
|---|---|
| Undulator period | 0.3 mm |
| Deflection gradient | 2 GeV/m |
| Undulator strength | 0.14 |
| Undulator length | 12 cm (400 periods) |
| FEL center wavelength | 0.1 Å (120 keV photons) |
| FEL pulse duration | 5 attos |
| Rayleigh range | 25 mm |
| FEL gain length (effective) | ~13 mm |
| Effective pierce parameter | $\sim 5 \times 10^{-3}$ |
| Pulse energy | ~200 nJ |

## 4. Overview of the proposed device

The previous sections described the proposed dielectric undulator and its expected FEL operation. However, this is the downstream-most component of a device that requires an electron beam with a unique emittance and longitudinal pulse structure. The properties of the required electron beam parameters listed in Table 1 are not realizable with conventional accelerators and electron sources. Therefore, a description of the envisioned electron source and accelerator is presented.

Field emission tips appear to offer an attractive possibility for the generation of ultra-low emittance electron beams with a MHz repetition rate. In particular, laser-driven field emission tips show additional promise of electron beams with a sub-fs time structure. Such tips can emit well-collimated electron bunches from a nanometer area with a divergence angle of 10° [16], which corresponds to a geometrical emittance of $\sim 5 \times 10^{-10}$ mrad. However, these were made with relatively low peak current beams, and due to the small transverse and longitudinal dimensions of these electron bunches from these laser-driven tips emittance and energy spread growth from space charge effects are expected to be a major limitation even with fC-scale bunch charges. Therefore, a key challenge for the successful development of a technology that includes such field emission tips as electron sources is likely to include an adaptation of bunch-shaping techniques commonly found with high-charge RF guns.

A further challenge will be the development of a low-energy accelerator that captures the nonrelativistic electrons from the field emission source and brings them to relativistic, few-MeV kinetic energies. The pre-accelerator is likely to be an optical microstructure qualitatively similar to the relativistic accelerator sections that are already under development, but designed to provide an optical accelerating field whose phase velocity is matched to the accelerating electron bunch and whose speed is steadily changing throughout the structure. The successful development of this element is arguably the most challenging step in the realization of an ultra-low emittance, optically bunched electron source for the proposed undulator.

The accelerator sections are already under development and several different architectures are presently being researched.

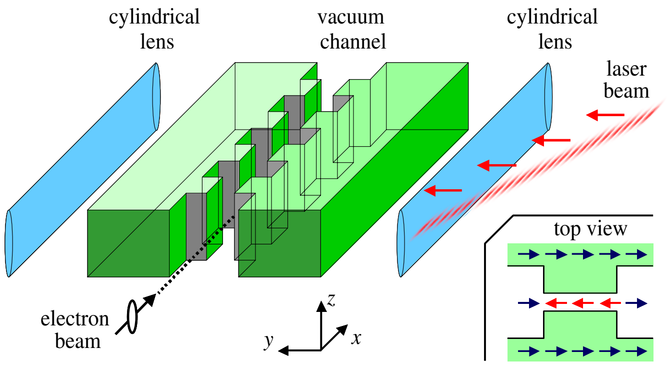

**Fig. 4.** A proposed dielectric-structure laser-driven accelerator that is compatible with the proposed undulator.

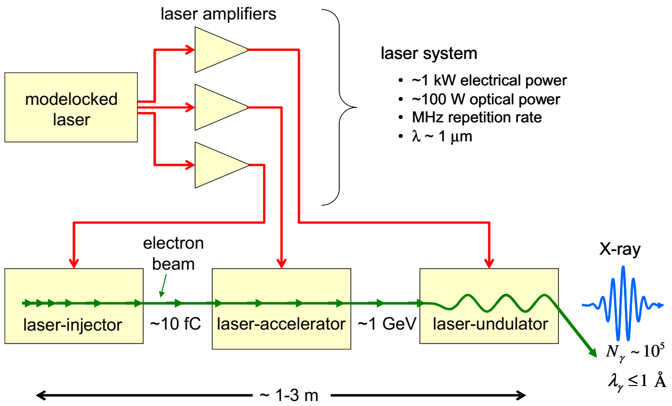

**Fig. 5.** The proposed X-ray device.

Fig. 4 shows a diagram of a possible accelerator structure that is compatible with the proposed undulator shown in Fig. 1. This accelerator structure is also pumped transversely by a pulse-front tilted beam, but due to the orientation of its groove pattern on the vacuum channel it only supports a phase-synchronous acceleration force [8].

In sum, all the components from the laser-driven injector to the proposed undulator are envisioned to be dielectric-structure microcomponents compatible with MEMs technology and are furthermore expected to be driven by the same high-repetition rate laser system. Fig. 5 shows a diagram of the entire system, including the drive laser.

The laser system is likely to consist of a stable, low-power modelocked oscillator that is followed by an array of moderate-power amplifiers that provide laser power to individual millimeter-long sections of the injector, accelerator and undulator. For an electron beam with the parameters of Table 1, the total electron pulse energy of 20 fC at 2 GeV is $4\times10^{-5}$ J/bunch. Assuming an optimum coupling efficiency of ~10% between the laser field and the electron bunch at optimum beam loading, a corresponding laser pulse energy of ~$4\times10^{-4}$ J/bunch will be required. Such a pulse energy is compatible with standard kHz-repetition rate Ti:sapphire regenerative amplifier systems. However, for this specific application a laser architecture based on the master-oscillator, power-amplifier (MOPA) concept is more appropriate. Single-pass, moderate-power fiber-based amplifiers that can maintain optical phase stability appear ideal, since they will allow for MHz repetition rates and are compatible with compact and effective heat removal technologies. Assuming a one MHz repetition rate, a fiber-based MOPA laser with a 10% wall plug efficiency would require ~5 kW of electrical power to drive the proposed tabletop X-ray source.

The technologies required for the proposed X-ray source are in their very early development stages. Furthermore, due to their miniature scale there will be a long research and development effort, and consequently the realization of the proposed X-ray source lies in the distant future. Nevertheless, the prospect of a meter-scale, coherent X-ray source derived from this technology for applications that require a stable, high-repetition rate photon beam is worth exploring.

## Acknowledgments

The authors thank R. Ischebeck, P. Hommelhoff, E. Colby and Z. Huang for valuable advice on various aspects of the proposed concept. We also thank Northrop Grumman for its support and funding of this work.

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