DEGINE OF PHOTONIC CRYSTAL ACCELERATOR FOR BASIC RADIATION BIOLOGY

A. Aimidula[#], K. Koyama, Y. Matsumura, M. Uesaka, The University of Tokyo,
2-22 Shirakata-Shirane, Tokai, Naka, Ibaraki, 319-1188
T. Natsui, M. Yoshida, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305-0801

Abstract

We are aiming at application of photonic crystal accelerator to on-chip electron beam source for fundamental radiation biology. Its aspects of nm beam size and as short pulse have a potential to be used for microscopic and ultra-fast analyses of damage and repair of radiation-irradiated DNA and chromosome. Output electron energy, beam intensity and device-size would be MeVs, fCs and a few cm, respectively. Here we present our first results of numerical analysis for design of the accelerator. We are determining the dimensions of dual grating based acceleration structure. We have also analytically estimated required laser parameters. Finally, we propose a system consisting of electron injector and multi-stage accelerator structures, which is really a miniaturized optical linac.

INTRODUCTION

Since the transverse dimensions of acceleration cavity of Photonic crystal accelerators (PCA) are on the operating laser wavelength scale, they are able to deliver nm-beams of sub-fs pulses. These high quality beams have an irreplaceable advantage in investigating the basic radiobiology process by shooting a single DNA [1]. There are three candidates for photonic crystal accelerator structures, dual-grating structure, photonic crystal fiber and woodpile structure [2]. Development of nano-technology let the fabrication more precise and cheap. SLAC demonstrated the high acceleration gradient in their latest experiment [3]. In this paper, we introduced a new dual-grating based structure, the original idea comes from Plettner's structure [4], we slightly changed the position of pillars, it also can efficiently modify the laser field. The basic principle of the dual grating acceleration structure is decreasing the phase velocity of the oscillating electric field by introducing periodically spaced small dielectric pillars and synchronize the field oscillation from non-relativistic to relativistic electron energies.

aimidula@nuclear.jp

DIMENSIONS AND FIELD DISTRIBUTION OF ACCELERATION STRUCTURE

The proposed structure cross section geometry and dimensions are shown in Figure 1. The lattice length is λ, the pillar and vacuum length equally $1/2\lambda$, λ the wavelength of operating laser. Driving laser lights are fed from the two outer surfaces (the red surfaces), electrons move in the vacuum channel perpendicular to the laser traveling direction. The laser light goes through the structure, the speed in the grating pillar is lower than that in the adjacent vacuum space. This produces the desired π-phase-delay and periodic electric field distribution inside the vacuum channel along the longitudinal beam axis. Figure 2 shows the z-component of the electric field distribution (the z-axis is the longitudinal beam direction). Along the vacuum channel, each region of opposite vibrating field are equally $1/2\lambda$, and then the relativistic electrons can catch up with the vibrating field which its phase velocity equal to light speed in vacuum and be accelerated. The pillar height and vacuum channel-gap are determined by the simulation. For electric field calculation we used CST MICROWAVE STUDIO®. Figure 3 shows that this two side feeding mechanism efficiently decrease the transverse field (x-component, perpendicular to particle traveling direction) which is unfavorable for the longitudinal acceleration. For the laser wavelength, we choose 800 nm. Many dielectric materials have good transparency at this wavelength. Material for the accelerator structure is chosen with respect to its transparency range, electric field damage threshold, thermal conductivity, nonlinear optical coefficients, chemical stability and refraction index. In our simulation, we select diamond, which has an index of n=2.36, since high-indexed dielectric materials can lead to higher accelerating gradients [4].

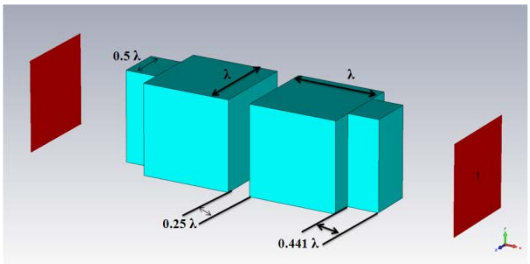

Figure 1. Dual grating structure dimensions.

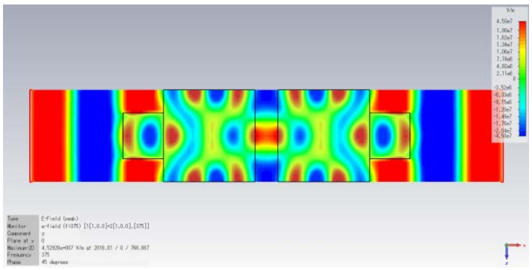

Figure 2. E-field (peak) z-component (accelerating field) distribution, colors represent the field strength and directions.

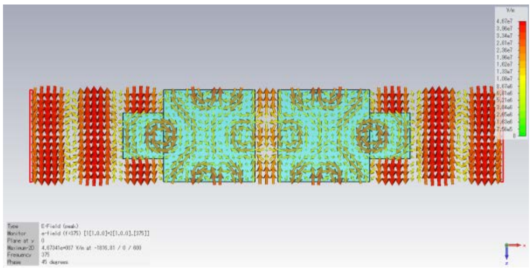

Figure 3. Arrow map of electric field distribution

ACCELERATION GRADIENT AND LASER REQUIREMENTS

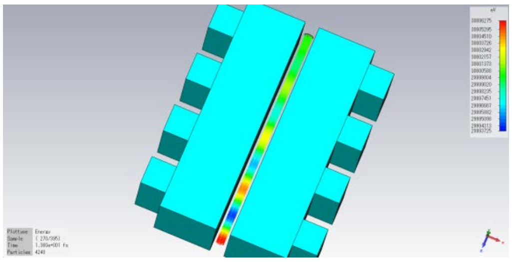

Figure 4. Particle track simulation

We have obtained the acceleration field gradient by the particle track simulation using CST PARTICLE STUDIO. Acceleration gradient is 1.9 GeV/m for an unloaded field of 7.9 GV/m so that about 1/4 of the maximum electric field is converted into the average acceleration gradient. One of the advantages of the dielectric laser accelerators is that the dielectric materials can sustain higher electric field. For laser pulses below 1 ps, the damage threshold of dielectric grating structure has been measured to be ~2 J/cm^2 [5]. Figure 4 shows the electron movement along the vacuum channel. Initial electron energy is 30 MeV, beam diameter is 128 nm, current is 50 mA. We have also analytically estimated the required laser parameters to feed a 10-mm-long structure from one side. By these information in Table 1, we can find that fiber lasers are the best selection for the light source. They have their unique advantages such as compactness, stability, no needs for cooling, high repetition rate and low cost.

Table 1. Required laser parameters to pump one centimeter long strcture and required initial particle energy

Pulse energy	20 μJ
Average power	2 kW
Pulse width	100 fs
Repetition rate	100 MHz
Initial electron energy	30 MeV

FUTURE PROSPECTS AND CHALLENGES

To make a compact accelerator structure, we should decrease the size of electron injector. For example, rather small power supplier of 60 kV is recently available [6]. The problem is how we synchronize such low energy electrons with fast changing field. The transit time of the electrons across the period of the grating structure must be equal to the time-period of the laser light. Figure 5 describes our multi-stage acceleration scheme. Parameters for lattice constant of the grating and initial speed of injected electrons are under investigation. Beam loading in hundreds-nm-wide and few-cm-long vacuum cavity is going to be analyzed in the next step.

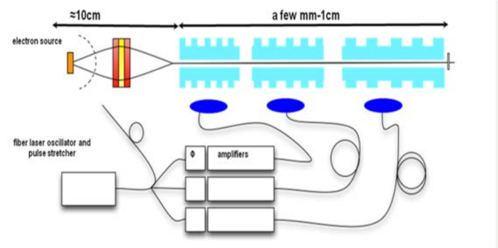

Figure 5. Schematic figure of multi-step acceleration.

CONCLUSION

Dielectric laser accelerator is suitable for investigating the basic processes of the radiation effect in the biological cell. We present our initial results on the first step preparation for the dielectric laser acceleration experiment. We found optimum grating parameters for relativistic particle acceleration. Dual grating lattice constant is one laser wavelength, pillar and vacuum length are equally half laser wavelength, The maximum acceleration field gradient appears when the pillar height and vacuum channel gap equal to 0.441 and 0.25 laser wavelength, respectively. To accelerate low energy particles we need to adjust the structure dimensions to decrease the phase velocity.

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