A PROPOSAL TO DEVELOP ELECTRO-OPTICAL DETECTION
FOR THE TEMPORAL CHARACTERIZATION OF
SUB-PICOSECOND BEAM BUNCH*

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1.0.0 Report for the experiment # 1042511

Title: *A proposal to develop electro-optical detection for the temporal characterization of sub-picosecond beam bunch*

1.0.1 Authors

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Other Investigators: R. Burns, D.M. Lazarus, Y.K. Semertzidis, T. Srinivasan-Rao, and T. Tsang Brookhaven National Laboratory

1.1.0 Purpose To develop a novel, single-shot, non-destructive method of determining the time structure of the relativistic electron bunch length in the sub-picosecond resolution. Using an electro-optical flash (EO-flash) detection technique, we will demonstrate that the electron bunch length can be converted from time to spatial information.

1.2.0 Approach A relativistic electron beam produces an anisotropically directed, radially extended Coulomb field orthogonal to the electron beam direction shown in Figure 1.1. Thus the relativistic contracted Coulomb field provides an accurate representation of the longitudinal charge distribution in a beam bunch. When this ultrashort Coulomb beam field traverses a birefringent crystal, the refractive index ellipsoid is modulated and an optical phase shift is introduced. This time dependent changes in the birefringence at different spatial location can be probed by focusing a synchronized femtosecond light pulse to a line focus on the EO crystal. Using a pair of crossed polarizer, this induced optical phase shift is converted to an intensity variation along the line focus. Therefore the temporal shape of the electron bunch is transformed to a spatial intensity distribution on a linear CCD detector array, hence EO-flash technique, illustrated in Figure 1.2.

Fig. 1.1 E-field after Lorentz contraction

Fig. 1.2 Schematic of the EO-flash technique

The experiment is to be done at the Accelerator Test Facility (ATF) and the Source Development Laboratory (SDL) at the Brookhaven National Laboratory. Both facilities use rf photoinjector for the electron beam production. The electron beam source at ATF is a 45 MeV beam in a bunch length of ~ 0.5 picosecond after compression with a single bunch charge of up to 250 pC capable of focusing to a beam size of $\sim 200 \mu\text{m}$ in diameter. While the SDL is a 200 MeV beam in a bunch length of ~ 100 femtosecond after compression with a bunch charge of 600 pC. Electron beam field will be analyzed by a thin $10 \times 10 \times 0.25 \text{ mm}$ ZnTe $\langle 110 \rangle$ single crystal.

1.3.0 Technical progress

1.3.1 EO experiment at ATF

At the ATF facility, the rf photoinjector light pulse is 6 ps long which is much longer than the anticipated 0.5 ps electron beam bunch to be measured using the EO technique. In order to characterize a sub-picosecond electron beam a sub-picosecond light pulse is required. We have identified a femtosecond Yb-glass laser oscillator at the ATF as the photon source in our EO detection scheme. The synchronization of the electron beam and the light pulse has been achieved by phase-locking the master rf clock of the ATF to the Yb-glass femtosecond laser. This passively mode-locked laser emits at the center wavelength of 1.05 μm with an average optical power of 100 mW at the repetition rate 81 MHz in a pulse duration 210 fs FWHM. Therefore it has 1.2 nJ/pulse with a peak power of ~ 6 kW/pulse.

Fig. 1.3 ATF photoinjector upgrade configuration

Fig. 1.4 Yb-doped fiber amplifier

Using a Pockels cell a single pulse was successfully sliced out of the phase-locked pulse train to be used for EO measurement. However, the laser oscillator alone delivers only $\sim 10^9$ photons/pulse for EO measurements. Considering at best EO signal modulation of 10%, a 10^{-4} extinction after cross polarizers, and an optical loss of 50%, we anticipated only $\sim 10^4$ signal photons to be observed on a CCD in a line focus. For a 512 pixel element CCD, each pixel receives only ~ 23 signal photons riding on 10 times more unmodulated (dc) photons. Significantly more photons are needed to achieve good SNR after image processing. Therefore, effort is being made and necessary equipment are required to amplify the light pulse from 1 nJ to ~ 10 μJ using one or two stages of fiber amplifiers, see Figures 1.3 & 1.4. The IR light pulse will then be frequency doubled to the visible spectrum and send to the EO measurement station. A linear 1-D diode array will be used to collect the spatial intensity distribution. Image subtraction

with and without the electron beam will be performed to obtain the electron bunch length information.

A first stage fiber preamplifier was built at ATF. The system compiles of a 980 nm fiber pump laser presently emitting 16 Watts of cw power, a 1.5 meter long Yb-doped double clad large-mode-area gain medium. After fiber coupling, 6 Watts of pump laser enter the fiber gain medium. The 200 fs seed laser emits at the center wavelength of 1054 nm with an average output power of 120 mW and a repetition rate of 82 MHz. The throughput of the seed laser in the fiber gain medium is 16%, resulting in 19 mW of unamplified average output power. The single pass amplified output power reaches 500 mW of average power. Thus the amplified gain is ~ 25 with an output energy of ~ 30 nJ per pulse. Presently the pump power was not completely absorbed in this short 1.5 meter length of gain medium. Since the gain has an exponentially dependence on fiber length, it's anticipated that a gain of 100 can be achieved in the first preamplifier. Effort has been made to incorporate a longer gain medium in this system. At the completion of a second stage fiber amplifier, the energy per pulse should reaches a few μJ sufficiently intense for the EO-flash experiment. A free space optical beam transport will be designed for use in the experimental hall at the ATF facility. Experimental beam test will be conducted around October of 2006.

Fig. 1.5 First-stage fiber amplifier

1.3.2 EO experiment at SDL The SDL at the NSLS provides a high brightness subpicosecond electron beam bunch length with several hundred Amperes peak of beam current. The SDL accelerator consists of a photoinjector, four SLAC-type accelerating structures for up to 200 MeV beam energy, and a magnetic chicane compress the beam to hundred femtoseconds. The facility has two undulators and a short modulator for self amplified spontaneous emission (SASE) and high gain harmonic generation (HG) experiments. An advantage of running the EO-flash experiment at the SDL facility is that a synchronized 100 femtosecond Ti:Sapphire laser system is already in place as a seed for the FEL and HG experiments. Unlike ATF facility, no laser development work is required prior to the EO-flash measurement. The frequency tripled Ti:Sapphire was used to generate several hundred pC of charge from a copper photocathode at a repetition rate of up to 5 Hz limited by the rf power amplifier. More than 1 mJ/pulse at a compressed seed pulse of 100 femtosecond is available to serve as a seed for the HG and FEL experiments. Therefore, a fraction of the compressed seed pulse is adequate for the EO-flash experiment. Figure 1.6 shows the construction of the EO-flash experiment. This experimental setup is installed between the first spectrometer dipole after the accelerator and the modulator magnet of the HG experiment, where a temporal and transverse overlap of the electron beam and the seed laser can be established. The induced birefringence in a ZnTe crystal by the Coulomb field of the electron beam is probed, the schematic is shown in Fig. 1.7. The temporal profile and the timing jitter between electron beam and seed laser will be observed. A

motor-controlled mount holds a 10x10x0.5 mm thick ZnTe crystal, a 100 μm thick YAG crystal for e-beam monitoring, and the optics to direct the seed beam to the EO crystal, all contained in a compact EO detection module shown in Fig. 1.8. Depending on the mount's position, the entire EO-flash setup can be inserted to provide nondestructive single-shot measurements of the bunch shape or it can be retracted to allow unobtrusive beam propagation to seed the FEL amplifier downstream. A CCD camera monitor from top down the position and the status of the EO crystal, shown in Fig. 1.9.

Fig. 1.6 EO cell under construction at SDL

Fig. 1.7 Schematic of the EO setup

Fig. 1.8 EO-flash module

Fig. 1.9 Top down view of ZnTe Eo crystal

The complete EO-flash module and the necessary optics was installed at SDL on March 2006, see Fig. 1.10. First e-beam test run using the EO-flash module was performed on at SDL on May 2006. The intensity of the 120 fs NIR light was attenuated to $\sim 1 \mu\text{J}/\text{pulse}$ prior to irradiated on the EO crystal with a 8 mm length line focus to $\sim 25 \mu\text{m}$ using a $f=15 \text{ cm}$ cylindrical lens. Because the femtosecond NIR pulse is linearly polarized, a $\lambda/4$ waveplate is used to convert the light pulse to circular polarization for the EO measurements. The modulated output beam is collimated using another $f=15 \text{ cm}$ cylindrical lens followed by a Glan-Taylor polarizer to select the modulated component of the light pulse. Finally, ND filters are used to prevent saturation on the linear detector. A $f=25 \text{ cm}$ cylindrical lens focus the modulated light onto a linear 1-D diode array. The temporal-to-spatial conversion is detected by performing subtracting the signal with and without the present of the 200 MeV electron bunches. Because of the constant present of accelerator related electronic noise, signal subtraction is rather, yet the noise subtraction remains imperfect. Fig. 1.11 shows the result before and after noise subtraction. The oscillatory behavior is believed partly due an uncoated focusing optics in the beam path and mostly the uncoated vacuum window. There are some challenges to locate the correct timing synchronization

between the NIR probe beams with the electron beam. Within experimental accuracy, the EO modulated signal was not observed in this first beam run, however, necessary experimental details were established. We anticipate resolving these issues in the next beam run at the end of August 2006.

Fig. 1.10 EO setup installed at SDL

Fig. 1.11 First beam test run results

1.4.0 Conclusions

Optical technique based on EO modulation has the potential to greatly advance micro-bunch diagnostics in electron accelerators in a non-destructive manner. Using the well-known techniques in the characterization of femtosecond laser light pulse, femtosecond electron pulse can be completely characterized. One of our goals is to develop this EO-flash diagnostic arrangement simple and compact enough so that we can transport it easily from one accelerator facility to another for various electron bunch length measurements. We have bench test our EO-flash at the SDL facility and will subsequently continue the effort at the ATF facility. We've meet some experimental challenges and would like to resolve the timing synchronization issue in the next scheduled beam run at SDL. Upon the successful completion of this experiment, single-shot sub-picosecond electron bunch length will be determined and EO-flash scheme will be utilized as noninvasive, standard, electron beam diagnostic equipment on the beamline. We will then demonstrate the portability and the reliability of the system and the accuracy of the measurement technique at various other accelerator facilities.

2.0.0 Report for DoE grant # ER41326 Part I

Title: *Advanced Topics of Particle Acceleration in Vacuum with High-Power Lasers*

2.0.1 Authors

Principle Investigator: I. Ben-Zvi, State University of New York at Stony Brook and Brookhaven National Laboratory

Other Investigator: Levi Schachter, Department of Electrical Engineering Technion - Israel Institute of Technology, Haifa 32000, Israel

2.1.0 Purpose Motivated by the availability of solid-state lasers with increasing wall-plug to light efficiencies, optical acceleration of charged particles is a subject of recent interest. An example of an open optical structure is the LEAP [1] crossed laser beam accelerator where the interaction between the crossed laser beams and the particles is limited by slits to satisfy the Lawson-Woodward theorem [2-3]. A different concept is the dielectric waveguide, an example of which is the two-dimensional *photonic band-gap* (PBG) structure where a laser pulse is guided in a dielectric structure with a vacuum tunnel bored in its center [4]. Recently, it was suggested to use Bragg reflection waveguides, designed specifically for the speed-of-light mode, as acceleration structures [5]. Optical Bragg acceleration structures, planar or cylindrical, having typical transverse dimensions of a few microns, exhibit high performance as acceleration structures and therefore seem to be promising candidates for future optical accelerators. In this study, we focus on the *planar* optical Bragg acceleration structure depicted in Fig. 2.1.

Figure 2.1.: Planar optical Bragg acceleration structure.

2.2.0 Approach Transition from operation at radiation wavelengths of a few centimeters to a few microns, requires examining a wide spectrum of phenomena which are insignificant in the former regime. An aspect that may have a critical impact on the performance of a dielectric acceleration structure and is being investigated in the framework of the present program is the heat dissipation and the temperature increase linked to electromagnetic power loss.

Consider the planar optical Bragg acceleration structure shown in Fig. 2.1. The structure may support an accelerating gradient of the order of $E_A \approx 1$ [GV/m] at a typical radiation wavelength of $\lambda_0 \approx 1$ [μm]. We assume that a train of laser pulses is injected into the acceleration structure, and it is the goal of this study to establish the temperature dynamics within the structure. For simplicity, in this section it is assumed that the dielectric layers have *identical* thermal characteristics, and the dissipated power across the device is approximated by its general behavior as given in Ref. [5]. Consequently, we may develop an analytic result, which is an approximation of the full solution. In the following section, the different thermal characteristics of the layers, and the exact behavior of the electromagnetic field are accounted for.

The power propagates at the speed-of-light mode, having a transverse profile $X_0(x)$, which is determined by the detailed geometric and electrical characteristics of the structure as well as the vacuum wavelength. For the planar optical Bragg acceleration structure, the transverse profile may be approximated by [5] $X_0(x) \propto \exp[-2(x - D_{\text{int}})/x_c]$, where $x_c = (\lambda/4) \left[(\epsilon_1 - 1)^{-1/2} + (\epsilon_2 - 1)^{-1/2} \right] \left| \ln \left[\epsilon_1 (\epsilon_1 - 1)^{-1/2} / \epsilon_2 (\epsilon_2 - 1)^{-1/2} \right] \right|^{-1}$; ϵ_1 is the permittivity of the layer adjacent to the core, and the remainder of the layers are alternating with materials ϵ_2 and ϵ_1 . Each pulse has a time duration T_p which is of the order of picoseconds, and they are separated by intervals of T_{rr} that, in turn, may vary from microseconds to nanoseconds. The pulses travel at a group velocity V_{gr} , and have a temporal profile of $T_0(t)$, so that for the simple case of a rectangular pulse, the temporal profile of the power density may be represented as a Fourier series $T_0(t) = \sum_{\nu} f_{\nu} \exp(j2\pi\nu t/T_{\text{rr}})$, where $f_{\nu} = (T_p/T_{\text{rr}}) \text{sinc}(\pi\nu T_p/T_{\text{rr}})$ and $\text{sinc}(u) \equiv \sin(u)/u$. The temperature developed inside the structure is due to the dissipated electromagnetic power given by $P_{\text{loss}} = \frac{1}{2} \omega \epsilon_0 \epsilon_r \tan \delta (E_x^2 + E_z^2)$, where $\tan \delta$ is the material loss tangent. Consequently, the dissipated power may be written in the form $P_{\text{loss}} = P_0 X_0(x) T_0(t - z/V_{\text{gr}})$. Based on Ref. [5], the field in the vacuum tunnel, having a time dependence of $e^{j\omega t}$ is of the form $E_z = E_A \exp\left(-j\frac{\omega}{c}z\right)$, and accordingly, the peak value of the dissipated power may be approximated by

$$P_0 \propto \frac{1}{2} \omega \epsilon_0 \epsilon_1 \tan \delta E_A^2 \left[1 + \left(\frac{1}{\epsilon_1} \frac{\omega}{c} D_{\text{int}} \right)^2 \right]. \quad (1)$$

All the characteristic time-parameters of the electromagnetic problem are orders of magnitude shorter than that corresponding to the diffusion process. The latter controls the temperature variation ΔT throughout the system described by

$$\left(\frac{\partial}{\partial t} - \frac{1}{D} \nabla^2 \right) \Delta T = \frac{1}{D \sigma_T} P_{\text{loss}}, \quad (2)$$

where D is the diffusion coefficient, and σ_T is the thermal conductivity. It is assumed that at some location $x = D_{\text{ext}}$ the structure is in thermodynamic equilibrium with a "heat-sink" which maintains a constant temperature $\Delta T(x = D_{\text{ext}}) = 0$. In addition, there is no heat-flow from the dielectric to the vacuum, and thus we ignore radiative heat transfer and assume $[\partial \Delta T / \partial x](x = D_{\text{int}}) = 0$. Subject to the above conditions, the diffusion equation may be solved analytically.

The transverse heat-flow may be derived from the temperature by $Q = -\sigma_T \partial \Delta T / \partial x$. Two quantities of interest are readily evaluated: the *average* change in temperature (ΔT_{AV}) over the repetition rate period of the pulse (T_{rr}) at the vacuum dielectric interface ($x = D_{\text{int}}$), and second,

the average heat-flow (Q_{AV}) at the external layer ($x = D_{ext}$). These two quantities were evaluated to read $Q_{AV} = \left(P_0 \frac{x_c}{2} \right) \frac{T_p}{T_{rr}}$,

$$\Delta T_{AV} = \left[\frac{P_0}{\sigma_T} \frac{x_c}{2} (D_{ext} - D_{int}) \right] \frac{T_p}{T_{rr}} \left[1 - \frac{x_c}{2(D_{ext} - D_{int})} \right] \square \left[\frac{P_0}{\sigma_T} \frac{x_c}{2} (D_{ext} - D_{int}) \right] \frac{T_p}{T_{rr}} \quad (3)$$

where the right hand side was evaluated assuming that $D_{ext} - D_{int} \square x_c/2$, a condition that may be dictated in part by the requirement for mechanical strength of the structure. Assuming $D_{ext} - D_{int} \square x_c/2$, the thermal trans-conductance has a very simple form, $Q_{AV} / \Delta T_{AV} \square \sigma_T / (D_{ext} - D_{int})$, which is virtually independent of the electromagnetic characteristics of the structure (x_c). In order to investigate the above results, we shall consider a silica-zirconia structure ($\epsilon_1 = 2.1, \epsilon_2 = 4$) with a set of parameters given in Table 1. Fig. 2.2 illustrates the two quantities Q_{AV} and T_{AV} as a function of the core half-width D_{int} . The curves are computed assuming that the field on axis remains constant ($E_A = 1$ [GV/m]), so that the dissipated power P_0 changes with D_{int} . Both quantities are linearly dependent on the material loss tangent and their value at $D_{int} = 0.2[\mu\text{m}]$, is $\Delta T_{AV} = 1.94 \times 10^8 \tan \delta$ [$^\circ\text{K}$], and $Q_{AV} = 3.21 \times 10^9 \tan \delta$ [W/cm^2]. Evidently, for the range of core half-widths shown in Fig. 2.2, if $\tan \delta < 10^{-8}$, the temperature rise in the structure is less than $15[^\circ\text{K}]$, and the average heat flow is about $250[\text{W}/\text{cm}^2]$. While the *average* quantities ($\Delta T_{AV}, Q_{AV}$) do not seem to pose a difficulty provided $\tan \delta \leq 10^{-8}$ simulations indicate that neither the *peak* temperature or heat flow pose an stringent constraint.

Table 2.1: Parameters used for the simulations shown in Fig. 2.2.

Structure parameters		Pulse and thermal parameters	
λ_0	1[μm]	T_p	1[psec]
ϵ_1, ϵ_2	2.1, 4.0	T_{rr}	1[nsec]
x_c	2.68[μm]	σ_T	1.4[$\text{W}/\text{m}^2\text{K}$]
D_{ext}	10[μm]	D	$1.2 \times 10^6[\text{sec}/\text{m}^2]$

Figure 2.2: The average change in temperature ΔT_{AV} and the average heat-flow Q_{AV} as a function of D_{int} , for a silica-zirconia structure with the parameters given in Table I. Both quantities are normalized to their value at $D_{int} = 0.2[\mu\text{m}]$, $\Delta T_{AV}(D_{int} = 0.2\mu\text{m}) = 1.94 \times 10^8 \tan \delta$ [$^\circ\text{K}$], and $Q_{AV}(D_{int} = 0.2\mu\text{m}) = 3.21 \times 10^9 \tan \delta$ [W/cm^2].

2.4.0 Conclusion We have analyzed the temperature and heat-flow across a planar optical Bragg acceleration structure. An approximate dynamic analysis showed that for the range of parameters of interest, it is sufficient to consider the steady-state problem, rather than account for high repetition rate pulses. Approximate *analytic* expressions for the steady-state temperature and heat variations were given. Assuming an accelerating gradient of 1[GV/m] and a low-loss material similar to that existing in communication optical fibers $\alpha \approx 1$ [dB/km], resulting in a loss tangent of the order of $\tan \delta \approx 10^{-11}$, the temperature increase is less than 1°K, and the heat-flow is of the order of 1[W/cm²]. This heat flow is three orders of magnitude lower than the known technological limit, implying that according to this preliminary analysis, proper choice of materials may eliminate thermal considerations from the list of obstacles for the operation of an optical accelerator.

The complete study was published in Physical Review Special Topics: Accelerators and Beams and its copy may be found at the end of this report.

3.0.0 Report for DoE grant # ER41326 Part II

Title: *Electromagnetic Forces on a Planar Optical Bragg Acceleration Structure*

3.0.1 Authors

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3.1.0 Purpose Optical Bragg acceleration structures [5], either planar or cylindrical, having typical transverse dimensions of a few microns, exhibit high performance as acceleration structures and therefore seem to be promising candidates for future optical accelerators. In the present study, we focus on the *planar* optical Bragg acceleration structure. The laser light is guided between two mirrors in a vacuum core, as shown in Fig. 3.1. The mirrors consist of dielectric layers with alternating permittivity, having transverse quarter-wave width with the exception of the innermost layer. This first layer is a *matching layer* whose width is determined so that the structure supports the speed-of-light TM mode required for the acceleration process.

Fig. 3.1: Configuration of the planar optical Bragg acceleration structure.

3.2.0 Approach It is evident that if accelerators are to work at optical wavelengths, then the acceleration structures will be about 3 orders of magnitude smaller in the narrow transverse dimension of the cross section than current structures driven by microwave sources, as the structures will be made of micron-scale dielectrics instead of centimeter-size metallic walls. At the same time, the electromagnetic fields due to the traveling wave will be significantly stronger. Moreover, since the overall amount of charge is expected to remain similar to that of current accelerators, the electromagnetic wake-field resulting from the motion of these charges will be stronger as well. These intense electromagnetic fields exert forces on the dielectric structure, commonly referred to as "radiation pressure".

Both the accelerating laser field and the wake-field resulting from the moving charges inside the structure contribute to the pressure on the dielectric layers. The accelerating charges are likely to be arranged in a train of bunches due to efficiency constraints [6]. Through a detailed analysis of the wake-field in the optical Bragg acceleration structure, we have shown that the impact of the wake on the structure is almost solely due to the fundamental electromagnetic propagation mode, which is the mode in which the accelerating laser pulse propagates. This analysis, which uses the residue theorem in the wake-field integral, emphasizes the distinction between open structures,

such as the Bragg structures, and closed structures such as the dielectric loaded planar transmission line. In open structures, moving charges excite a large number of modes, most of which are leaky by nature, exponentially decaying behind the bunch, contrary to closed structures, where truly guided modes are excited. Nevertheless, in both cases the deceleration force on a single particle is identical, depending only on the vacuum tunnel width and the permittivity of the adjacent dielectric layer.

In a Bragg structure with vacuum core width of 0.6 wavelengths, for instance, the fundamental mode is responsible for only 30% of the deceleration force. This may lead to the erroneous conclusion that the remainder of the modes may have a significant impact on the structure. However, our analysis shows that the non-fundamental modes have a relatively strong exponential decay, or may be guided modes with very small amplitudes. Consequently, the impact that results from the non-fundamental modes is considerably smaller than that of the fundamental. It is also evident that the Bragg structure has an advantage over the closed dielectric loaded planar transmission line. The latter structure consists of two metallic walls with a dielectric layer adjacent to each and a vacuum core. The advantage of the Bragg structure is that for the same train of electron bunches, the amplitude of the fundamental mode it excites is lower, thus less interfering with the acceleration of trailing bunches in the train, and creating a smaller impact on the structure.

Since we demonstrated that the fundamental mode, which is due partly to the driving laser and partly to the wake-field, is responsible for virtually all of the electromagnetic forces on the structure, it is sufficient to use a cw analysis in order to examine the possible implications on the acceleration structure. This analysis is based on calculating the Lorentz force densities on the polarization effective currents and charges [7] within the dielectric layers. For example, the volume force densities for two Bragg structures are presented in Fig. 3.2. The frames in the left column correspond to a structure having the SiO_2 as the layer adjacent to the core, and the right column corresponds to a structure with Si as the layer adjacent to the core. When the lower refractive index is used for the first layer, the maximum of the volume force density is obtained inside the second layer, whereas in the second case, the maximum is obtained inside the first layer.

In addition to the volume forces densities, surface force densities arise at the interfaces between the dielectric layers due to polarization surface charge densities. The total internal pressure at some point within the layers against an external mechanical enforcement is given by the cumulative sum of both surface and volume force densities starting from the vacuum core up to the point of interest. This pressure is also depicted in Fig. 3.2. It is seen that in the layers that are close to the vacuum core, the pressure is negative, pulling these layers towards the core. Farther away from the core, the pressure becomes positive and approaches $\epsilon_0 E_0^2 / 4$, E_0 being the accelerating gradient, not seen clearly in the figure due to the scale.

Fig. 3.2: Volume force densities in two Bragg structures made of SiO₂ (indicated by lighter gray) and Si. a)-(b) Two of the electromagnetic field components, (c)-(d) volume force densities, and (e)-(f) total internal pressure. The left column frames correspond to a structure with SiO₂ as the first layer, and the right column corresponds to Si as the first layer.

Since the total transverse pressure on one of the Bragg mirrors is $\epsilon_0 E_0^2 / 4$, if we consider an accelerating gradient of $E_0 = 1 \text{ [GV/m]}$, then this pressure equals $2.2 \times 10^6 \text{ [N/m}^2\text{]}$. Assuming that one Bragg mirror in the structure has an area of $1\text{mm} \times 1\text{mm}$, the total transverse force on the mirror is 2.2 N. For a mirror thickness of $50\mu\text{m}$ and material density of about 2gr/cm^3 we obtain that this force is 6 orders of magnitude larger than the gravitational force on the mirror, showing that the radiation pressure is by no means negligible.

On the other hand, from the perspective of material strength and the possibility of crack formation, the situation is different. The order of magnitude of the pressures in the Bragg structure including the internal pressure is $10^6 - 10^7 \text{ [N/m}^2\text{]}$. According to rough theoretical estimates, it would be reasonable to assume that an internal pressure below E/π , where E is Young's modulus, may be sustained without damage to the structure [8]. Young's modulus for SiO₂ is $72.6 \text{ [GN/m}^2\text{]}$, whereas for Si it is $162 \text{ [GN/m}^2\text{]}$ [9]. It follows that the electromagnetic pressures in the structure under consideration are at least 3 orders of magnitude below the theoretical threshold E/π . We, therefore, conclude that under the assumptions considered here, the electromagnetic forces in the Bragg acceleration structures do not pose a threat to the dielectric layers.

4.0.0 References

- [1] Y. C. Huang, D. Zheng, W. M. Tulloch and R. L. Byer, "Proposed structure for a crossed-laser beam, GeV per meter gradient, vacuum electron linear accelerator", *Applied Physics Letters* 68, 753-755 (1996).
- [2] J. D. Lawson, "Lasers and accelerators", *IEEE Transactions on Nuclear Science* NS-26, 4217-4219 (1979).
- [3] P. M. Woodward, "A method for calculating the field over a plane aperture required to produce a given polar diagram", *Journal of IEE* 93, 1554-1558 (1947).
- [4] X. E. Lin, "Photonic band gap fiber accelerator", *Physical Review Special Topics – Accelerators and Beams* 4, 051301 1-7 (2001).
- [5] A. Mizrahi and L. Schächter, "Optical Bragg accelerators", *Physical Review E* 70, 016505 1-21 (2004).
- [6] L. Schächter, "Energy Recovery in an Optical Linear Collider", *Physical Review E* 70, 016504 1-13 (2004).
- [7] J. Schwinger, J. L. L. DeRaad, K. A. Milton, and W.-Y. Tsai, *Classical Electrodynamics* (Perseus Books, Reading, MA, 1998), p. 39.
- [8] B. Lawn, *Fracture of brittle solids* (Cambridge University Press, UK, 1995), 2nd ed.
- [9] M. Bass, E. W. Van Stryland, D. R. Williams, and W. L. Wolfe, *Handbook of Optics Volume II* (McGraw-Hill, New York, 1995).

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