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Q-SWITCHING OF X-RAY OPTICAL CAVITIES BY USING BORON DOPED BURIED LAYER UNDER A SURFACE OF A DIAMOND CRYSTAL

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Abstract

Improvement of the longitudinal coherence of X-ray Free Electron Lasers has been the subject of many recent investigations. The XFEL oscillator (XFELO) and Regenerative Amplifier Free-Electron Laser (RAFEL) schemes offer pathways to fully coherent, high brightness X-ray radiations. The XFELO and RAFEL both consist of a high repetition rate electron beam, an undulator, and an X-ray crystal cavity to provide optical feedback. The X-ray cavity will be based on diamond crystals in order to manage a high thermal load. We are investigating a 'Q switching' mechanism that involves the use of a 'Bragg switch' to control the X-ray pulse energy built-up and outcoupling inside the X-ray cavity. In particular, one can use an optical laser to manipulate the diamond crystal lattice constant to control the crystal reflectivity and transmission. It has been shown that a 9 MeV focused boron beam can create a buried layer, approximately 5 microns below surface, with a boron concentration up to 10^{21} atoms/cm^3, with localized and enhanced optical absorption. Here, we present simulations showing that absorbing laser pulses by a buried layer under the crystal surface would allow creating a transient temperature profile which would be well suited for the 'Q switching' scheme.

INTRODUCTION

The brightness of x-ray sources has been increased one to ten billion times by x-ray free-electron lasers (XFELs) that generate high intensity coherent photon pulses at wavelengths from nanometers to less than one angstrom and a duration of a few to 100 femtoseconds [1]. For the first time XFELs allow for experimental exploration of the structure and dynamics of atomic and molecular systems at the angstrom-femtosecond space and time scale. This have created a plethora of new opportunities for scientific research in physics, chemistry, biology, material science and high energy density physics [1, 2]. A characteristic feature of single-pass SASE FELs, however, is the poor longitudinal coherence, which results from the initial amplification of incoherent radiation shot-noise [1]. Improvement of the longitudinal coherence is of great practical importance and has been the subject of many recent investigations. With high repetition rate machines, such as European XFEL [3], and LCLS-II [4] coming online soon, an XFEL oscillator (XFELO) [5, 6] or Regenerative Amplifier Free-Electron Laser (RAFEL) [7, 8] offers a pathway to the production of stable, fully coherent, high brightness, and high average power X-ray radiation. These so-called cavity-based X-ray free-electron lasers (CBXFELs) consist of a high repetition rate electron beam, a short undulator, and an x-ray crystal cavity (in the case of hard X-rays) to provide optical feedback (Fig. 1).

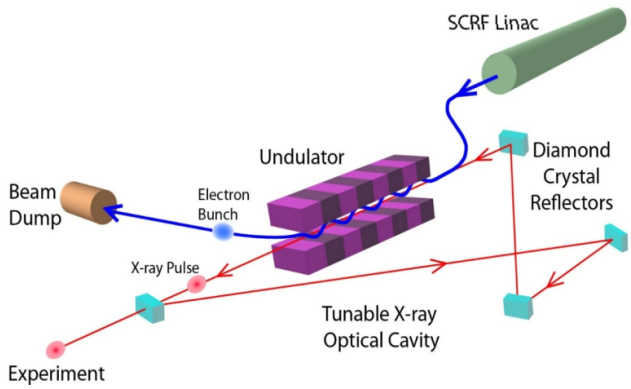

Figure 1: Schematic illustration of an X-ray cavity for XFELO or RAFEL. Four crystals form a closed X-ray cavity via Bragg reflection [9].

Q-SWITCHING OF X-RAY OPTICAL CAVITIES

Like optical laser cavities, outcoupling optics and mechanisms is one of the essential components, which can come in the form of a partial reflector or cavity 'dumper'. We are investigating the viability of a 'Q switching' mechanism that involves the use of a 'Bragg switch' to dump the x-ray pulse energy built-up inside an x-ray cavity [10, 11]. The idea of Bragg switching by a controlled lattice deformation using piezoelectric excitation, generation of optical and acoustic phonons or picosecond thermal excitations has been proposed and demonstrated at synchrotron sources by several authors [10–18]. However, the construction of an x-ray cavity around a high repetition rate XFEL will require using materials that can manage high thermal load. Single crystal diamond is a good candidate as it has superb thermal and mechanical properties and, because it is a low Z material, X-ray energy deposition per volume is much less than other candidates such as silicon crystal [19]. Therefore techniques that have been already proposed cannot be applied directly here as our choice of materials is limited to low Z materials and the XRAFEL cavity output-coupling techniques needs further studies.

In this work we investigate the use of optical laser to manipulate the crystal lattice constant in such a way that the crystal reflectivity/transmission can be controlled by the relative timing of the optical laser excitation and the

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arrival of the x-ray pulse, as well as laser power. Unlike the previous work [18] that reported a picosecond scale response time, here the goal is to make use of a much longer time window, and find the optimal parameters for minimizing impact on the reflected x-ray wavefront, so that the beam can be re-circulated back to the entrance of the undulator and deliver the highest possible seed power. The key for the optimization of the CBXFEL performance using this 'Q switch' scheme is to find the best way of controlling the temporal-temperature profile close to the crystal's surface, as well as keeping the spatial-temperature profile uniform over the x-ray beam footprint.

As an example, we present here investigation of transient thermal excitation of the diamond lattice constant achieved through short pulse optical laser excitations. The lattice spacing, therefore, can be manipulated to satisfy or not satisfy the Bragg reflection condition at desired times. The thermal transport time scale of absorbed energy out of the primary absorption region in the crystal is 10's of ns due to the high thermal conductivity of diamond. This is significantly shorter time scale compared to the projected pulse repetition rate of the supconducting LINAC driven sources at 1-5 MHz, which enables the possibility for pulse to pulse control of the crystal reflectivity in order to realize a 'Q switch' for the cavity.

While the most obvious route was to use an optical laser pulse to switch the pre-aligned crystal away from the Bragg condition, in order to to render the whole crystal non-reflecting which dumps the cavity power-buildup, lattice constant would need to be changed throughout the crystal thickness. As the time scale of switching in this case will be partially governed by the thickness of the crystal, thin diamond crystal plates with thickness on the order of the crystal reflection extinction depth will need to be used. This will introduce further challenges in crystal fabrication, mounting, and cooling. An alternative approach, as illustrated in Figure 2, allows the use of thicker crystals. In this rectangular cavity setup, we maintain all crystals except for the out-coupling crystal at an elevated temperature T_1 and aligned to Bragg condition at 90°. Instead of using a laser pulse to switch the crystal *off*, we propose to use the synchronized laser pulse train to maintain the surface temperature to match the other crystals, while the rest of the outcoupling crystal stays at a lower temperature T_2. The temperature and lattice constant distribution when the x-ray arrives at the out-coupling crystal can be controlled both by the power and the timing of the laser pulse, in order to achieve best reflectivity and minimum wavefront distortion for the closed cavity configuration shown in Fig. 2(a). When one wants to dump the cavity, the heated region can be turned *off* by changing the laser parameters (power, timing) for the corresponding laser pulse. The x-ray pulse returned to the outcoupling crystal can therefore transmit through as shown in Fig. 2(b) with a very small absorption loss. With this scheme, a high quality thick crystal can be used, while still allow fast switching time scale.

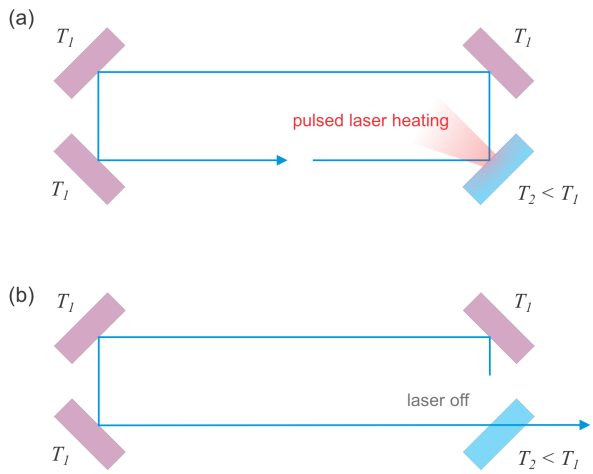

Figure 2: (a) Configuration of the closed cavity. The lower right crystal is kept at lower temperature. A synchronized laser pulse is used to control the surface temperature and lattice constant to meet the Bragg condition. (b) configuration of an open cavity with the laser switched OFF. The lower right crystal at lower temperature would thus become transparent to the 'resonant' wavelength.

One challenge to achieve high reflectivity of the outcoupling crystal is to establish a transient uniform temperature profile over the depth of the extinction length of ~5 μm (assuming 9.8 keV photons using the (400) reflecting planes at a 45° Bragg angle). Initial simulations including a time-dependent thermal transport analysis of the diamond crystal assuming energy deposition directly on the surface using near-band-gap UV wavelength has shown that it is rather difficult, as shown in Figure 3 (top). Here we propose a novel scheme to enable a more uniform temperature profile. It has been shown [20] that by using 9 MeV focused boron beam one can create a buried layer, approximately 5 microns below surface, with a boron concentration up to 10^{21} atoms/cm^3. Such concentration levels should be sufficient to absorb infrared laser pulses [21] and would allow improved control of a desired temperature profile close to the surface. The compatibility with an IR instead of UV pulse also simplifies significantly the laser setup requirement. The time dependent temperature profile from the absorbed IR light at the depth of the implanted boron in a diamond crystal is shown in Figure 3 (bottom) and it indicates that a uniform temperature profile can be obtained. A collaboration with colleagues at Universidad Autonoma de Madrid to use the CMAM microbeam line to perform boron ion implantation has been initiated. In the first phase of this investigation, HPHT type IIa diamond crystals will be characterized both before and after boron ion implantation to ensure a high diamond crystal quality can be sustained. Experimental measurements are planned for FY20. A second phase of the investigation includes testing the Bragg switching concept with these implanted diamonds in a time-resolved experiment, and later in a 20-m-round-trip cold cavity at the LCLS using the XPP

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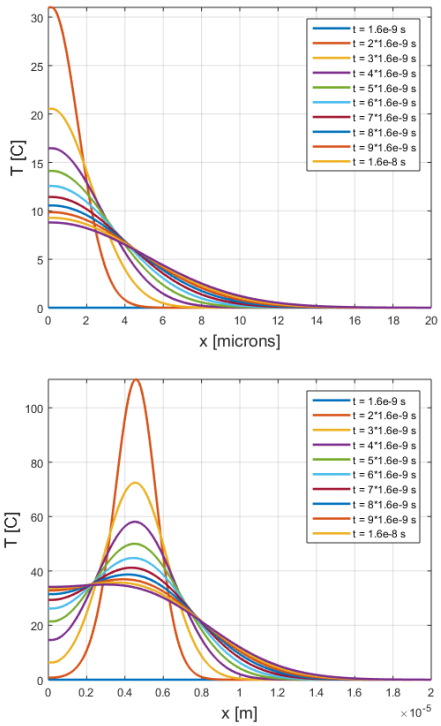

Figure 3: Time dependent thermal profile into the crystal from surface heating (top) and time dependent thermal profile into the crystal of a boron doped diamond (bottom).

experimental hutch [22]. Time domain thermal mechanical modeling will also be performed considering potential future average and impulsive thermal loading, for Q-switch optimization.

DIAMOND CRYSTAL CHARACTERIZATION

White beam topography can be used as an initial characterization, e.g. at the Advanced Photon Source (APS) at Argonne National Lab. At the BM-1 beamline white beam topography setup, a collimated polychromatic synchrotron X-ray pulse is sent onto the diamond crystal sample and multiple Laue reflections are captured on the X-ray film downstream. The film is then developed and digitized for analysis. White beam topography, while not providing enough information about the reflection surface, is a very fast and efficient technique to quickly locate the primary defects such as inclusions, dislocations and stacking faults within the diamond crystals, which usually appear as brighter features on the image due to their broader wavelength acceptance and sometimes multiple re-scattering of the X-rays. To quantitatively determine the potential locations for the boron ion deposition, we calculate the RMS variance map of the obtained white beam topography images.

We apply a circular mask, with a size corresponding to about 3σ of the X-ray beam size, and scan it across, retaining the values of mean and variance of integral intensity. In addition, we determine the areas connected by <5% difference

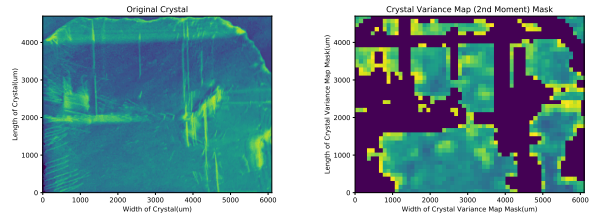

Figure 4: Left: white beam topograph of a type IIa diamond crystal. Right: variance maps with masked potential doping areas

in variance with the neighboring points. As a result, we produce a crystal map of the areas, concurring both for doping and possible CBXFEL tests [23]. The variance as a function of position on the crystal is then plotted in color in Fig. 4. We note that spatial resolution and non-linear gain of the film is an important limiting factor for higher quality topographs. Therefore, we will use the resulting variance maps as a guidance for ion deposition, while rely on monochromatic beam topography for crystal quality assurance. The results of these studies will be reported elsewhere.

Ideally monochromatic beam rocking curve analysis to be performed before and after the ion deposition to access the impact of the implantation to crystal surface by evaluating the rocking curve height and width in a spatially resolved way. In addition, the angular variation in the rocking curve center is a reflection of the residual mechanical strain of the crystal lattice. This angular variation must be minimized to preserve the transverse coherence of the reflected beam in an oscillator application, in addition to achieving high reflectivity. We believe both white beam and monochromatic beam topography measurements are important to fully characterize the diamond samples in order to identify the best region on the highest quality diamond crystals for CBXFEL applications.

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