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Bending diamonds by femtosecond laser ablation

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ABSTRACT

We present a new method based on femtosecond laser ablation for the fabrication of statically bent diamond crystals. Using this method, curvature radii of 1 m can easily be achieved, and the curvature obtained is very uniform. Since diamond is extremely tolerant to high radiation doses, partly due to its densely packed lattice, such bent crystals are optimal solutions for crystal-based collimation and/or extraction. Furthermore, using interlaced ablation on both sides, the technique opens for the possibility of constructing a crystalline undulator based on the best material known, to approach the enormous beam densities required for lasing operation of such a device.

1. Introduction

Since its prediction [1] and the first experiments in the late 1970s, the use of and knowledge about particle channeling in bent crystals has increased steadily and is now at a well-established stage where almost all aspects of the phenomenon have been covered. However, for a possible application of the phenomenon as an extraction [2] or collimation [3] device at the LHC at CERN, it is mandatory that the crystal from which the device is made, is able to tolerate extreme radiation doses, being exposed to the tough environment near the main beam. Diamond is such a material, but has hitherto proven almost impossible to bend, being rigid and brittle. We present in the following a method to bend diamonds to the desired shape, relevant for implementation as an extraction and/or collimation device. In this connection, the unusually high thermal conductivity of diamond combined with its high melting temperature, yields yet another advantage compared to, e.g. silicon, see [4] for a discussion of some of the benefits of diamonds.

Measurements were performed in the mid-1990s showing that the deflection efficiency in silicon deteriorated by $6 \pm 2\%/10^{20}$ p^+/cm^2 [5] and diamond is expected to be much more radiation hard, having a much denser lattice than silicon (a ratio of lattice constants of only 0.66). Electron densities of the order 10^{21} cm^{-3} have been available at the Final Focus Test Beam (FFTB) at SLAC and theoretical schemes to increase this by a factor 30 have been devised [6]. It is known from experimental tests at SLAC that a diamond crystal bears no visible influence from being irradiated by the FFTB, whereas aluminum simply evaporates [7]. At the LHC, the crystal being positioned in the beam halo some 6–7 σ away from the beam center, the intensity is expected to be about 10^9 p^+/s. Nevertheless, occasionally the crystal will intercept much higher intensities and must be able to withstand high doses.

2. Channeling in bent crystals

In the so-called continuum approximation [8], charged particles incident on a single-crystal with small angles to crystallographic directions, experience the collective fields as if smeared along the string or plane. If, further, a particle has sufficiently low transverse momentum with respect to the axis or plane of the crystal it can be

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restricted to areas away from the nuclei (positively charged particles) or close to the nuclei (negatively charged particles). In this case the particle is channeled and is guided by the lattice such that a separation of the longitudinal and transverse motions is present. The result is a conserved 'transverse energy' and therefore a transverse potential in which the particle moves.

The guidance of channeled particles persists even if the crystal is slightly bent, such that the particle may be deviated from its original direction of motion as in a dipole magnet. Since the fields that are responsible for this deviation are the extremely strong (screened) fields present near the nuclei, the corresponding bending power can reach a magnitude equivalent to a magnetic field of several thousand Tesla.

For a review of this effect as well as of its applications at high energy accelerators, see [9,10].

2.1. Extraction and collimation devices

Originally, studies of deflection of charged particles in bent crystals were performed using so-called three- and four-point bending devices to bend the crystals [11–14]. However, to minimize curvature and multiple scattering dechanneling in the crystal, a method was developed to achieve a nearly uniform curvature on Si crystals – evaporation of a ZsO layer on top of the face perpendicular to the curvature [15]. Other methods, e.g. U-shaped crystals cut from large ingots and bent by mechanical means were also tried to obtain uniform curvature in extraction experiments [16]. However, none of these methods are applicable (or at least they are prohibitively costly) for diamond.

As a part of the development of these extraction devices, it was soon realized that so-called multi-pass extraction is an important phenomenon in crystal-based extraction [16], at least for protons [17]. Multi-pass extraction is a mechanism by which particles that encounter the crystal and are not channeled will not necessarily be lost and may be extracted on a later turn in the machine. The importance of the multi-pass mechanism results in the optimum length for an extraction device being significantly shorter than for a single-pass mechanism [18], e.g. from cm to mm for TeV beams, allowing for the use of diamonds.

2.2. Crystalline undulators

A number of methods have been proposed to generate a periodically shaped crystal suitable for the generation of crystalline undulator radiation. Among these can be mentioned acoustic waves [19], graded composition strained layer superlattices [20] and crystals where the surface has been mechanically manipulated in a periodic fashion by either scraping [21], etching, implantation, growing [22] and now laser ablation. As shown in the following, the latter is an accurate method – both in terms of trench spacing, homogeneity and depth-reproducibility. Far better than the scraping technique – for obtaining the desired surface properties, even for a material as hard as diamond. It has recently been shown that such surface-manipulated structures suffer from the serious drawback that the perturbations to the lattice are not uniform through the bulk [23], in line with expectations from early measurements [21]. However, as long as the imposed period is not much smaller than the crystal thickness, undulator-type radiation should be observable and fairly monochromatic [23]. Furthermore, recent experimental proof that crystalline undulator radiation exists [24], even from electrons penetrating a crystal much thicker than the dechanneling length, shows that studies on a lasing effect in crystalline undulators – or even a gamma klystron [25] – are on the verge of being experimentally accessible. However, for such devices, a radiation hard material is unavoidable, making further studies of diamond desirable.

3. Synthetic diamonds

Diamond can now be synthesised at unprecedented levels of purity and lattice quality for plate dimensions of up to $5 \times 5\ \mathrm{mm}^2$ (up to 1 mm thickness), and in certain conditions, somewhat larger. This synthetic diamond material comes in two broad classes, which we may term CVD and HPHT diamond, based on the method of synthesis. Both these material types are studied for the micro-crystalline undulator application. Diamond for high end electronic applications is preferentially produced by Chemical Vapour Deposition (CVD), using a high quality single-crystal diamond substrate [26]. Impurity incorporation and intrinsic defect formation may be excluded quite substantially. In the best cases, the most important impurities, boron and nitrogen, are essentially at few- or even sub-ppb levels. An indication of the quality is that the charge collection distance, which is relevant to electronic applications, may be several times longer than typical device dimensions, and the carrier mobility approaches the theoretical value. However, although impurities are well controlled, the relatively low growth temperature ($\simeq$750 °C) means that relatively little annealing occurs during growth and the residual lattice strain is in the order of 10^{-6}. There are also sparse bundles of dislocations with relatively large defect free volumes. Optical diamond is preferentially synthesised by the temperature driven reconstitution method using high quality seeds at High Pressure and High Temperature (HPHT) [27]. Getters may be used to control impurities, however, the concentrations of boron and nitrogen are difficult to maintain below levels of some tens of ppb. In this case, the residual strain in the lattice, which is relevant to X-ray optical applications at modern synchrotrons and X-ray Free Electron Lasers (FELs), is in the region of 10^{-8}. This optimal value is achieved for the cubic growth sector in plates extracted as far as possible from the seed. The region of highest lattice quality is then typically up to $4 \times 4\ \mathrm{mm}^2$ [28–32].

The diamond lattice has several characteristics that make it an important material for investigations in this respect. The lattice is extremely radiation hard as discussed above. This consideration is of special importance for a material that could conceivably sustain the beam bunch intensities for the SASE version of the micro-crystalline undulator. The high Debye temperature results in diminished lattice vibrations, which increases the dechanneling length. This also enhances the coherence length for phenomena where this is relevant. The low atomic number leads to a lower channeling potential but this is offset somewhat by the very high atomic packing. The $\langle 110 \rangle$ channeling direction in diamond is particularly favourable for the channeling of positively charged particles, as both the core distribution and the electron distribution contribute to a deep potential well which is well separated from sources of hard scattering.

In the case of CVD diamond of electronic quality, one aim is to explore the production of a diamond superlattice. The lattice dilatation would be due to regulated and graded impurity incorporation (boron and/or nitrogen). These impurities can be introduced during growth into the feed gas stream. There is already a certain amount of experience with such experiments, and it is known that high quality interfaces can be achieved. Of crucial importance is the preservation of lattice quality (residual strain) for larger concentrations of these impurities. The lattice dilatation for nitrogen (single substitutional) is better known, and is about [33]

$$\frac{\Delta a}{a_0} = (0.125 \pm 0.006) \times C_N, \tag{1}$$

where C_N is the nitrogen impurity concentration expressed as an atomic fraction. Variation of the concentration may be considered