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BEAM TRANSPORT IN THE CRYSTAL X-RAY ACCELERATOR

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Abstract A Fokker-Planck model of charged particle transport in crystal channels which includes the effect of strong accelerating gradients has been developed[1] for application to the crystal x-ray accelerator[2] and other crystal accelerator schemes[3]. We indicate the implications of the analytic solutions found for a harmonic channeling potential in Ref.1for the acceleration of particles in crystals. The crucial effects are the accelerating gradient and the multiple scattering which, because we consider only the acceleration of positive particles, is dominated by scattering from the valence electrons. In order to relax the constraints imposed by these, we have been exploring the application of novel materials to this problem. One candidate is porous Si and our investigation into this material which is as yet preliminary is discussed and other possible materials are indicated.

INTRODUCTION

Several recent investigations have considered the possibility of achieving very high accelerating gradients is acceleration schemes based on the use of the phenomenon of particle channeling in crystalline solids[4] to provide the focusing normally obtained from magnets in conventional accelerator technology. Because of the scales involved, these accelerators would be powered by x-rays. In the so-called crystal accelerator concept, the crystal would act as a slow wave structure for the x-rays by analogy with conventional rf accelerators and the longitudinal component of the radiation field would provide the acceleration[2]. Another idea would use the laser beatwave concept or its variations to drive a longitudinal plasma wave in the solid which would then provide the accelerating field[3]. Accelerating gradients as high as 100 GeV/cm are, in principle, possible.

There are many issues which must be addressed in order to reduce any of these concepts to a viable accelerator scheme. In general terms these involve the beam transport in the crystal, the x-ray optics in the crystal and the crystal survivability. Of course, these are not independent. in particular they are coupled through the required accelerating gradient. We have investigated the first issue in Ref. 1 and will recap the results in the next section. Certain questions related to the x-ray optics of the crystal x-ray accelerator have been addressed in Ref. 2. Here it is established that the optical field required for particle acceleration can be, in principle, obtained. In the third section of this paper, we discuss our investigation of the application of novel materials to crystal accelerator concepts. Here we will mention the issue of crystal survivability using arguments discussed in Ref. 3. The areas for further research are discussed in the concluding section.

BEAM TRANSPORT

We have previously investigated[1] the transport of the particle beam in a crystal channel under the influence of the accelerating field, multiple scattering on the electrons in the channel and, for light particles, the reaction of the channeling radiation[6]. Although the radiation damping is useful in cooling the beam, the radiative energy loss is significant and a barrier is reached. The channeling of light particles under these conditions may be interesting as a radiation source however. We will confine our attention to heavy particles ($m \geq m_\mu$) and, because in the channeling of negative particles the multiple scattering is enhanced over that in a random medium, particles of positive charge.

The critical question for the beam transport is the distance into the crystal the beam can propagate before its rms angular spread due to multiple scattering exceeds the critical angle of scattering y_c (Ref. 4) :

$$\psi_c = a_c \sqrt{(2k/p)} \tag{1}$$

where a_c is the effective channel size, p is the particle momentum and k is the spring constant of the channel harmonic well both normalized to the particle rest energy. We have found the following result for the ratio of the mean square scattering angle to the critical angle for channeling:

$$\frac{\langle\theta^2\rangle}{\psi_c^2} = \frac{D}{2ka_c^2}\sqrt{\left(\alpha z/p_0\right)}\ , \tag{2}$$

where D is the momentum space diffusion constant normalized to the particle rest energy (the multiple scattering momentum diffusion coefficient is D/p^2, Ref. 1), p_0 is the initial normalized momentum, α is the normalized accelerating gradient and z is the distance of beam propagation into the crystal. A typical value of D for protons might be $D \approx 6 \times 10^{-7}\ \mathrm{cm}^{-1}$. As αz is essentially the final momentum, Eq. (2) defines a maximum final momentum in terms of the accelerating gradient and channel properties:

$$\frac{p_{max}}{p_0} = (2ka_c^2\alpha/D)^2 \tag{3}$$

With $k \approx 3\ \mathrm{eV/Å^2}$, an accelerating gradient of 100 GeV/cm and an initial momentum of 20 TeV, we have $p_{max} \approx 2000$ TeV.

NOVEL MATERIALS

In order to drive accelerating gradients of the order of 100 GeV/cm, it is estimated[2,6] laser power densities of the order of 10^{15}-10^{19} W/cm^2 would be required. The estimates in Ref. 2 indicate these power densities are sufficient to destroy the crystal in the beat wave scheme due to the ultimate decay of the plasma wave into phonons. In the crystal x-ray accelerator, the estimates of the laser fluence which would destroy the crystal is much more optimistic but this may depend more strongly on the details of the x-ray beam optics particularly the boundary conditions where the free space radiation couples to the crystal. In any case, we see from Eq. (3) that for a given final energy, a decrease in multiple scattering can be exchanged for a decrease in accelerating gradient and a consequent reduction in driving laser intensity. And, reduced scattering is of significance in its own right. Thus we have been led to consider materials in which a porous superstructure overlays the basic crystalline lattice. These kinds of materials are also of interest to the community investigating the possibility of generating stimulated radiation in the x-ray region by using the channeling radiation process[7,8]. They have suggested the possibility of using zeolites[9] while we have been led to begin investigating porous Si. This material has been of interest in the microelectronic device industry for several years having first been reported in 1956 following the anodization of a crystalline Si substrate[10]. That the underlying material remains crystalline[11] (with slightly increased lattice parameter) is important in our application. Furthermore the pore diameter can be controlled and is typically a few tens of Ångstroms.

Other properties of the pores which may be important to the channeling process are not now well understood. One question is the pore straightness. While the details of the electrochemical process are generally not important for our purposes, one feature may be of interest. The process requires the existence of holes and typically p-type Si has been used. However, the holes can be provided by the photoproduction of electron-hole pairs[12]. This may provide a way to control the pore geometry to tailor the material for channeling applications. There was also concern over the depth of the pores which could be fabricated. Recent work done at Sam Houston State University has etched up to 2 mm of Si and infrared Fourier transform spectroscopy indicates that the crystal has not been destroyed by the deeper etching. (Some IR spectroscopy results have been reported in Ref. 13.)

We are unaware of any investigation of particle channeling in either zeolites or porous Si. Because the pore diameter in the porous Si corresponds to about four unit cells, it is reasonable to speculate the potential well might be very flat, rising sharply near the pore edge. A similar behavior has been suggested for the zeolite pore[7]. If we use the estimate of dechanneling length in Ref. 7, it would suggest that the momentum space diffusion constant, D might be reduced by a factor of 10^2-10^3.

SUMMARY

While particle channeling in crystalline solids can provide strong focusing forces for an accelerating beam with multiple scattering reduced from that of the amorphous material, the scattering does impose severe constraints on the accelerating gradients needed. Novel materials in which the channeling takes place in pores in the crystalline substrate may be useful in reducing the multiple scattering. These are also of interest in the application of channeling to the production of stimulated x-radiation. These sources are of interest to crystal acceleration since this will require radiation in this wavelength regime to provide the "rf" drive. These materials may also be of interest in the application of particle channeling to accelerator beam "optical" elements[14]. However, mush research remains to determine the channeling properties of these materials. This should not only include channeling measurements on the transmission of heavy positive particles which are of interest in accelerator applications but also the channeling of both electrons and positrons. Here observation of the channeling radiation will be useful in understanding the channeling potential in the pores. Theoretical calculations of the transport can initially proceed on the basis of model potentials and be refined as the properties of the materials become better understood experimentally.

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