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Developments in Relativistic Channeling

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DEVELOPMENTS IN RELATIVISTIC CHANNELING

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Abstract

The possibility of using channeling as a tool for high energy accelerator applications and particle physics has now been extensively investigated. Bent crystals have been used for accelerator extraction and for particle deflection. Applications as accelerating devices have been discussed but have not yet been tried.

1. INTRODUCTION

Over the last decade there has been significant progress on the application of channeling to accelerators and high energy physics. Channeling extraction has turned out to be a remarkably interesting technique. Channeling has been used for beams at Serpukhov, CERN, and Fermilab and more possibilities continue to arise. Spin precession has been demonstrated at Fermilab but looks challenging for charm spin measurements. Development of simulation tools has continued, particularly for extraction. Channeling acceleration remains a dream but some interesting theoretical work and the advent of terawatt chirped lasers have drawn the curtain back further on an interesting possibility.

Recently there have been several excellent reviews of channeling by Biryukov et al. (BKC) [1] and Møller [2]. Many papers from a recent meeting on relativistic channeling will be available soon [3]. The following sections sketch basic channeling parameters, summarize applications to high energy beams and extraction, review proposals for acceleration, and consider exotic extensions.

2. BASIC CHANNELING PARAMETERS

Critical Angle: A particle no longer channels when the so-called critical transverse kinetic energy is equal to the channeling maximum potential energy U^m, that is:

$$E_{\perp}^{c} = \frac{1}{2} p\beta c\psi_{c}^{2} = U^{m} \qquad (1)$$

where ψ_c is the critical angle, p is the momentum, βc is the velocity, and U^m is the maximum potential. The Lindhard critical angle for planar channeling for a singly charged particle is:

$$\psi_{p} = \sqrt{\frac{4Ze^{2}Nd_{p}Ca_{TF}}{p\beta c}} \qquad (2)$$

where Z is the atomic number of the crystal, N is the atomic density, d_p is the planar spacing, a_0 is the Bohr radius, C is approximately $\sqrt{3}$, and a_{TF}, the Thomas-Fermi screening parameter, is equal to $0.8853a_0(Z^{2/3}+1)^{-1/2}$. At 1 TeV, ψ_p = 5 μrad for the (110) plane in silicon. Note that a channeling dip or peak is far from Gaussian. From the standpoint of applications a more useful quantity is $\psi_{1/2}$, the half angle at half width. This is roughly equal to the critical angle. Another factor that needs to be considered for some applications is the impact of lattice vibrations. Since these are temperature dependent the critical angle will vary with temperature [4]. This is particularly important for advanced accelerator applications where crystals might even vaporize.

Bent Crystal Channeling: The first serious suggestion that channeling in bent crystals could be used to steer charged particles was made by Tsyganov [5]. When a crystal is bent the potential well is modified by a linear centrifugal barrier. At a small enough bending radius, the Tsyganov radius,

$$R_T = \frac{E}{eE_c} \qquad (3)$$

the centrifugal barrier exactly equals the depth of the normal potential and particles are no longer captured into channeling orbits and deflected. Here E is the total energy and E_c is the interatomic field at a distance from the plane of the crystal lattice where the trajectory of the particle no longer remains stable due to its interaction with individual atoms. More complete treatments of bending dechanneling have been developed by Ellison [6], Kudo [7], and Kaplin and Vorobiev [8].

The equivalent magnetic field for channeling for the case $\beta \approx 1$ in a crystal bent with a uniform radius R is:

$$B = \frac{p}{0.3R} \qquad (4)$$

(here B is in tesla, p is in GeV/c, and R is in m). Equivalent fields up to 1000 tesla are feasible.

Dechanneling: Particles dechannel because of multiple scattering in the channel and defects such as dislocations. Although dechanneling is a diffusion process practically it can be described with a dechanneling length. For planar dechanneling BKC give:

$$\lambda_D = \frac{256}{9\pi^2} \frac{p\beta c}{\ln(2m_e c^2 \gamma / I) - 1} \frac{a_{TF} d_p}{r_e m_e c^2} \qquad (5)$$

where γ is the Lorentz factor, I is the ionization potential, d_p is the interplanar spacing, m_e is the mass of the electron, and r_e is the classical electron radius.

In a bent crystal the channeling potential is shallower and narrower. To account for this the dechanneling length for the straight crystal case should be multiplied by $(1-R_T/R_m)^2$ (see BKC). R_m is the minimum radius of curvature for the crystal.

Materials Issues: Materials affect every aspect of channeling. The planar critical angle is proportional to the cube root of the atomic number so that a high Z material like tungsten has a critical angle almost twice as large as silicon. The planar dechanneling length is less sensitive to Z but is proportional to the interplanar spacing, d_p, so that wide planes like $(111)_w$ increase the dechanneling length. The Tsyganov bending radius is inversely proportional to the critical field, that is Z^{-1}, so that tungsten should be better than silicon for bending.

A regular crystal structure, that is a lattice free of many dislocations, is imperative for high energy channeling. By far the best material in this regard is silicon. Presently available silicon single crystals should easily handle the energy of the LHC. Good germanium crystals are also available and have been used up to several hundred GeV. Tungsten is another matter. Available zone-refined crystals tend to be smaller and have more dislocations. A program is now underway at Dubna to develop better tungsten crystals [9].

A fourth material property that is important for some applications is the behavior in a high radiation environments. Tests with MeV-level channeling [10] found little significant degradation due to radiation damage up to fluences of $4 \cdot 10^{20}/\text{cm}^2$ in a 28 GeV proton beam. Since MeV channeling is more sensitive to induced point defects, high energy applications may be even less affected. A silicon crystal in a 70 GeV beam at Serpukhov [11] continued to channel with high efficiency after a fluence of more than $10^{19}/\text{cm}^2$ at an operating temperature of 150 °C.

Channeling Radiation: Particles moving in a crystal channel radiate much like they would in an undulator. The theory of channeling radiation was originally formulated by Kumakhov [12]. The channeling radiation maximum energy goes as $E^{3/2}$ for positrons in the 10 MeV to GeV regime. While this is a much higher energy than corresponding undulator radiation it is small compared to bremsstrahlung so there is no natural application of channeling radiation in high energy physics. However, recent work has emphasized the importance of channeling radiation as a damping mechanism for exotic accelerator applications (see later section on cooling).

The possibility of stimulated emission of channeling radiation has also been considered [13]. There has been no experimental progress on the subject. High but not un-realizable current densities would be required.

3. APPLICATIONS OF CRYSTALS AT HIGH ENERGY ACCELERATORS

Channeling in bent crystals has now been widely used at accelerators for both extraction and for secondary beam deflection. Transmission is the critical factor in applying a bent crystal. If the beam emittance is substantially greater than the crystal acceptance the transmission efficiency of a bent crystal in an external beam can be approximated by [14]:

$$E = E_c\left(\frac{\Phi_b^{50}}{\Phi}\right)\left(1-\frac{R_T}{R_m}\right)e^{(-sp_0/\lambda_{b0}p)} \qquad (6)$$

In the formula ϕ_b^{50} is the phase space acceptance of the bent crystal (proportional to the thickness times the channeling critical angle), Φ is the 50% phase space emittance of the particle beam for the crystal bending direction, E_c is the surface acceptance of the crystal, p is the beam momentum, s is the length of the crystal, and λ_{b0} is the bent crystal dechanneling length at p_0. As noted earlier, to account for the decreased channeling length in a bent crystal the dechanneling length for the straight crystal case should be multiplied by $(1-R_T/R_m)^2$. Both bending and temperature effects should be included in calculating the critical angle in the crystal acceptance so the critical angle (including lattice vibration effects) should be multiplied by $(1-R_T/R_m)$ as discussed by BKC. For a harmonic potential in a straight crystal when Θ_b (the beam divergence half width) >> ψ_c, BKC gives for E_c:

$$E_c = \frac{\pi x_c}{2d_p} \qquad (7)$$

where x_c, the critical transverse distance or effective half width of the channel, depends on the bend, screening, and lattice vibrations.

Up until now bent crystals have been used or considered for four major types of applications; external beam deflection, focusing, extraction from accelerators, and deflection and spin measurements of short-lived particles. These are discussed below.

External Beam Deflection: The first application of a crystal as a beam element appears to have been in 1984 in the Meson Bottom beam at Fermilab [15]. The peak energy of the beam had been 225 GeV limited by two 3 m long septum magnets. In a demonstration, these magnets were replaced by a 2.7 cm long crystal enabling the beam to go to 400 GeV. Use was constrained by safety considerations. The radiation safety experts were concerned that the crystal would work all together too well!

A bent crystal was also used at Fermilab as a beam throttle in NE operating at 800 GeV [16]. The crystal reduced the beam after a high intensity experiment so it could be used downstream in a low intensity emulsion experiment. The observed beam transmission was 0.05%, about a factor of six less than expected. The difference might have been due to some combination of misalignment of the body of the crystal relative to the planar direction, the onset of problems with dislocations or interstitial imperfections, overestimation of the surface acceptance, or an improper understanding of the crystal beam optics.

The most ambitious application of crystals to external beams is at Serpukhov where they have been applied in a variety of applications including beam splitting and beam diagnostics. Serpukhov (see BKC) holds the record for the largest deflection (150 mrad) and the longest crystal used (15 cm).

More recently a bent crystal has been used as a beam splitter to produce the K_S beam for CERN NA48, an experiment to measure CP-violation with high precision [17]. A much-attenuated proton beam is required to produce the K_S near the detection apparatus since the K_S decays quickly. Indeed, one challenge is reducing the beam by a factor of $0.5*10^{-4}$, well below a typical ratio of crystal channel phase space to secondary beam phase space. A second important consideration for the application has been the high flux on the crystal, on the order of 10^{12} protons every 14.4 s, leading to a fluence of $10^{18}/cm^2$ per year.

Focusing: Crystals can also be used as focusing elements. In the first multi-hundred GeV experiments at Fermilab losses were noted halfway around the bend in a three point bending jig. These losses were traced to additional local curvature due to the pressure of the middle bending pin. Sun suggested that this type of compression could be exploited to construct an element with a focal length of several meters [18]. A more straight-forward approach is to bevel the end faces of a bent crystal so that some rays are deflected more. In a beautiful series of experiments at Serpukhov, Smirnov and his colleagues [19] focused a 70 GeV proton beam down to a 40 micron line with a crystal with a 0.5 m focal length.

Spin Precession: The spin of a channeled particle moving in a bent crystal should precess through an angle ϕ given by:

$$\phi = \frac{1}{2}\gamma\omega(g-2) \tag{8}$$

for $\gamma >> 1$, where γ is the Lorentz factor, g is the gyromagnetic ratio, and ω is the deflection angle of the channeled particle [20]. This occurs because the crystal bend leads to an average electric field that points in to the center of curvature, resulting in a net effective magnetic field perpendicular to the plane of curvature. The spin of a particle moving in the channel precesses around that effective magnetic field.

In a recent Fermilab spin precession demonstration [21] polarized Σ^+ hyperons from the Fermilab charged hyperon beam were channeled in two silicon crystals with bends of ± 1.65 mrad (with an equivalent field of 45 tesla). These bends resulted in a spin precession of $60 \pm 17°$, in agreement with the predicted value of 62° based on the world average of the measurements of the Σ^+ magnetic moment. Improvements such as the use of crystals with more active area and five to ten times the bending angle would have permitted this experiment to match precision experiments done in the eighties.

Because they produce large deflections in a short length of crystal, the high effective magnetic fields associated with bent crystal channeling offer a unique possibility for the measurement of charm particle magnetic moments. On the other hand, the small angular acceptance for planar channeling is a significant limitation.

An experiment for a charm particle magnetic moment measurement would look quite different than the channeling Σ^+ measurement. Since charm lifetimes are short, there is not a beam of charm baryons in the conventional sense. In an experiment charm baryons would be produced in a thin, high Z amorphous target upstream of the bent crystal. An amorphous target is necessary since particles produced on nuclei in the channeling planes of a crystal cannot channel.

Daniels and Lach [22], Carrigan and Smith [23], and Samsonov [24] have studied the rates for a charm particle magnetic moment measurement. The conclusions from these studies are sobering. The physics is such that only two charm baryons, Λ_c^+ and Ξ_c^+, are likely to be measurable and both of them would have small precession angles. There is very little hope to measure beauty baryon magnetic moments since there are no relatively stable positively charged states. Conclusions about experiment running time depend sensitively on assumptions about how successfully one can trigger with a high intensity beam. The crystal bend could enrich the trigger, since the charm particles are deflected from the forward cone. The long-lived channeled particles go further around the bend so they will not be as large a background on the charm fraction of the beam. Samsonov has estimated that an experiment could be done in several hundred hours using a 10^9/s proton beam.

Extraction: Almost from the first suggestion of bent crystal channeling there has been interest in exploiting it for extraction from particle accelerators. The first demonstration of channeling extraction occurred at the JINR synchrophasotron at Dubna in 1984 [25]. Since relatively large particle beam deflections can be achieved with short crystals, an interesting feature of channeling extraction is to applications where the potential extraction path is limited. This feature has been exploited successfully at the 70 GeV Serpukhov accelerator where the available straight sections are short [26].

As usual the critical angle for channeling is a limitation. This is less of a problem for extraction than it would first seem since many unchanneled particles multiple scatter in the crystal and remain in the accelerator to channel on a later pass. This "multi-turn" extraction was first studied in simulations [27] and confirmed in experiments at 120 GeV at CERN [28].

For channeling extraction a crystal can be placed at the edge of the accelerator beam where it can extract a limited portion of the beam. This is particularly interesting for colliders where there may be enough halo to create significant external beams with little impact on the integrated luminosity. During the planning stages for the SSC such a technique was proposed to produce a 20 TeV proton beam suitable for beauty production [29]. A recent Fermilab experiment, E853, was undertaken at the Tevatron to investigate that possibility at 900 GeV [30]. E853 is the highest energy channeling experiment yet performed. No difficulties were experienced from such potential problems as dislocations or radiation damage.

Several mechanisms were used to pump halo beam onto the crystal. Beam-gas scattering and power supply modulation produced some natural beam growth. A fast kicker could provide transverse kicks of 0.5 mm at the crystal on an individual bunch. Beam diffusion on to the crystal was also stimulated with a fast horizontal damper. Finally, beam-beam collisions at the collider detector interaction regions stimulated halo beam growth and diffusion out to the crystal.

To study the effect of luminosity-driven extraction during E853 the circulating beams were prepared so that there were 36 proton bunches and three antiproton bunches in the Tevatron. This gave rise to 6 colliding bunches and thirty proton-only bunches. The E853 measurements found that the rate was roughly proportional to luminosity after the background was subtracted. The rates for colliding bunches were about 6 times higher than the proton-only bunches at a bunch luminosity of $0.4*10^{30}/cm^2s^1$. The effect of that luminosity was equivalent to moving the crystal into the beam on the order of 1 σ.

E853 made several different measurements of efficiency. One practical measurement of efficiency is the amount of beam extracted down the beam line divided by the beam lost in the accelerator. This measurement is not easy since determining the loss rate from the accelerator characteristically involves a difference between two large fitted numbers for beam lifetime in the accelerator. A second way to measure the efficiency is to determine the number of particles that interact with the crystal when it is not aligned versus the number that interact when it is correctly positioned for channeling. Calculations by Biryukov [31] predicted a practical efficiency of 30-45% for E853. The data for E853 not yet been completely analyzed but is slightly below the prediction. Efficiencies up to 15.4% were measured in a recent CERN 120 GeV run.

The beam that can be extracted from an accelerator using a crystal is limited by damage to the crystal, by the losses that can be incurred elsewhere in the accelerator and at the colliding experiments, and by the tolerable rate of beam current attenuation with time. For E853 beams of up to 0.5 - 1 M/s were obtained without significantly disturbing other operations and experiments.

Based on the E853 experience a design for a 1000 GeV, 100 KHz parasitic test beam for use during collider operations has been developed [32]. The beam, extracted at A0, would feed into the Fermilab fixed target areas. It has been designed for minimum impact on the existing complex rather than to optimize beam flux. The design makes use of two bent crystals, one for extraction with a bend angle of 16.4 mrad and another one with a bend of 7.5 mrad for redirecting the beam in to the switchyard. Because the angles are large, the transmission of the extraction crystal is 9% while it is 40% for the redirection crystal. The overall flux down the beam could be improved by using germanium crystals and perhaps bending less and adding more conventional magnetic elements to replace the second crystal and cut the bend required for the first one.

One other exotic application of extraction is the possibility of creating long base-line neutrino beams aimed toward large neutrino cosmic ray detectors [33]. While intriguing, dechanneling and small acceptance remain significant problems. Interestingly, unless physics dictates otherwise, there is no advantage in going to high energy to exploit linearly-rising neutrino cross sections because it takes longer to accelerate. Since the required deflection angles are large, there is a premium on high Z crystals. As with any neutrino beam, an expensive infrastructure of a meson decay pipe and a beam dump is required. In addition, any neutrino experiment requires a very large fluence of protons.

4. POSSIBLE APPLICATIONS TO ADVANCED ACCELERATORS

Over the past decades a number of suggestions have been made to apply channeling to advanced accelerator applications. The large electromagnetic fields, hundreds of times higher than laboratory fields, have the right feel for what is needed for an acceleration breakthrough. To be useful, channeling actually has to solve some problem like beam cooling. But channeling also comes with several penalties-the channeling critical angle is small, electrons cause dechanneling, negative particles don't channel well, and really high energy densities vaporize crystals.

Cooling: Beam cooling was one of first accelerator channeling applications to be discussed. A. Kanofsky [34] and E. Tsyganov, collaborators in the original Fermilab channeling experiment in the late seventies, raised the possibility of cooling particle beams with channeling. Radiative processes are significant for light particles and will be discussed in more detail later. At present energies radiative processes that can produce transverse cooling for heavy particles are small so that beam heating due to multiple scattering from the electrons in channels is the important process. In the early Fermilab investigations of axial channeling of heavy particles in a germanium crystal [35] heating was observed rather than cooling, as expected.

Channeling extraction raises the possibility of an alternative approach to cooling. Multiple-pass channeling extraction is like a cross between a Maxwell demon and the famous "Energizer Bunny" that just keeps going. The extracted beam has the low emittance of a crystal channel, potentially much smaller than an internal accelerator beam. Many particles that don't channel return and eventually channel. Of course some particles are lost to nuclear interactions and dechanneling. However if one could cut the beam size by 4-10 while losing half the particles there would still be a gain in luminosity if the beam was reused.

As an example, one could extract beam from the Fermilab Tevatron operating at 150 GeV into the Main Injector. The phase space would be reduced by the ratio of the critical angle to the beam divergence times the effective septum width divided by the beam size. This could be a factor on the order or 10. The extraction efficiency might be 25-50% so that the later luminosity gain would be several fold. There are several problems. One is that multi-pass channeling extraction requires multi-turn injection into the following accelerator or storage device, a challenging problem. A second is that this only works for positive particles. The third, and most challenging problem, is that handling the full accelerator beam does violence to the crystal and the accelerator.

It is possible to envision a system where the crystal "extracts" into a different part of the accelerator phase space. The crystal could kick the beam from one dip in a magnetic potential similar to a Higgs' potential in the Standard Model across an electrostatic septum into the other valley of the potential. After the entire beam had been "extracted" the electrostatic septum would be physically removed and the Higgs' potential would be adiabatically erased. Whether something like this is possible is debatable. The loss problem would be significant. For the E853 run and a 10^{12} proton beam the loss in the crystal due to ionization would be several Joules. Unless something was done such as moving the crystal or increasing the effective crystal septum width (which diminishes the effective beam cooling) the energy would be deposited in a small region so the temperature rise would be enormous. Much worse, 10^8 Joules would be lost somewhere else in the accelerator if the nuclear interactions losses were O(10%). This could easily quench a superconducting accelerator if it was lost in one place.

The possibilities for cooling positrons are more interesting. Recently Huang, Chen, and Ruth [36], [37] (HCR) have studied radiation damping in a continuously focusing planar channel. They find the particle damps down to a transverse ground state with a very small emittance of:

$$\gamma \epsilon_{min} = \hbar/2mc \qquad (9)$$

where m is the mass of the particle. Once the particle is in the ground state it can be accelerated without any radiative energy loss. The damping constant for the process is:

$$\Gamma_c = 2r_e K/3mc \qquad (10)$$

where K is the focusing strength of the channel, that is $V(x) = Kx^2/2$. HCR note that for a typical case $K = 10^{11}$ GeV/m^2 so that $1/\Gamma_c = 10$ ns. A 100 Mev particle in a crystal channel has an initial quantum number of about 500 so it requires 6 e-folding times to reach the ground state or 60 ns. This corresponds to a channel length of 18 m. At first blush, this is discouraging since the dechanneling length is much shorter. However HCR [38] argue that the channeling radiative damping rate suppresses both bremsstrahlung and transverse growth due to multiple scattering. In addition, if this process is used in conjunction with some advanced acceleration scheme it might be possible to accelerate fast enough to boost into a very long dechanneling length regime.

HCR illustrate the potential of this approach with an example of a 5 TeV on 5 TeV crystal collider. For 10^9 particles/bunch, 10 bunches in a train, and a repetition rate of 180 Hz they suggest the luminosity could be $L = 3*10^{36}$ cm^{-2}s^{-1} without the need for a final focus. The total beam power would be only 3 MW.

With the recent interest in cooling muons for muon colliders Bogacz, Cline, and Sanders [39] suggested channeling could be used for that purpose. Unfortunately the damping time for the HCR picture goes as the mass of the particle so that it is in the microsecond regime for muons. To overcome this problem, they suggest using an acoustic wave to set up a micro-undulator and get stimulated emission. In another approach [40], they propose exploiting ionization cooling in crystal channeling for muon cooling.

Acceleration: In the late seventies several suggestions were put forward for possible channeling accelerators using lasers. Some early proponents argued dielectric materials were needed to avoid electrical breakdown with the high laser accelerating fields. Kanofsky [41], apparently the first person to publish a concept for the application of channeling to acceleration, investigated a laser acceleration scheme suggested by Csonka [42] where a laser beam strikes a dielectric from the side. As noted by Kanofsky, the use of a channeling medium with acceleration along an axis minimizes scattering and energy loss and also exploits the transverse focusing of the channel. In the Csonka approach the crystal is masked so that the beam particles see only the in-phase electric field. Csonka estimated that purely laser acceleration could give accelerating gradients in the neighborhood of 0.1 GV/cm and would require laser power densities on the order of 10^9 W/cm^2. This approach has problems with diffraction and near-field effects. Kanofsky implicitly discussed dechanneling and seemed to recognize that acceleration would help to ameliorate the problem. However, since his laser acceleration gradient is "small" his estimates of transmission are extremely pessimistic. He did not consider the possibility of adiabatic damping of beam emittance later discussed by Chen and Noble [43].

Another early technique proposed by Grishaev and Nasonov [44] suggested a system of two coupled lasers to produce a longitudinal wave in a crystal with a non-linear optical susceptibility. They estimated the accelerating gradient would be 0.01-0.1 GV/cm. Both the lasers as well as the accelerated particle beam would have to be phase matched, a difficult problem over an extended acceleration region. Pisarev [45] discussed the use of a transverse laser swept along a crystal which would generate a static longitudinal electric polarization and "light rectification". Pisarev argued that this could produce phase matching. He estimated the accelerating gradient to be 0.04 GV/cm. The required power density was in the neighborhood of 10^{12} W/cm^2. Nasonov [46] suggested setting up a static charge distribution in alkali-halide crystals by driving a charge wave through atomic displacements with optical phonons. This delivers a relatively-modest gradient of 0.01 GV/cm. None of these people discuss dechanneling. Indeed, channeling considerations are a minor aspect of the three schemes.

Another variant of a laser-type accelerator in a modified charge distribution lattice has been proposed by Bogacz and his collaborators [47]. This scheme visualizes a strain-modulated lattice, either from a super-lattice or an acoustic wave. The modulated channel serves as an undulator in an inverse free electron accelerator [48]. Bogacz notes that too much undulator gain might cause rapid dechanneling. A typical acceleration gradient might be 0.03 GV/cm.

Belotshitskii and Kumakhov [49] studied both the physical limitations of the laser process as well as the efficacy of channeling for ameliorating the problems. They appear to have been the first to fully appreciate that rapid acceleration could overcome some of the problems with dechanneling. They also noted that in view of the short acceleration time the acceleration of unstable particles was possible. For the increase of transverse energy in a distance dx Belotshitskii and Kumakhov give:

$$\Delta E_{\perp} = e\kappa V_0 dx/E \qquad (11)$$

where κ is a coefficient that depends on crystal structure and is about 1 GV/cm for positive particles channeled axially, V_0 is the potential barrier for the channel, and E is the particle energy. To overcome the dechanneling it is necessary that the energy gain in dx, ΔE, be of the same magnitude as E. Chen and Noble treated this problem by using a dechanneling length that scaled with the total energy. They also introduced a normalized rms acceptance from accelerator theory:

$$\epsilon_{cn} = \frac{1}{2}\gamma a \psi_c \qquad (12)$$

where a is the axial channel radius and ψ_c is the critical angle. Note that this acceptance will scale as $\sqrt{E}$. They show that particles will remain channeled as they are accelerated provided the accelerating gradient $G \geq \Lambda^{-1}$, where $\Lambda = e\lambda_d/E$ is a normalized dechanneling length.

Belotshitskii and Kumakhov estimated the required power density for laser acceleration as 10^{15} W/cm^2 but also observed that crystal destruction occurs for power densities of 10^{11}W/g. They suggested that one way to address this problem was to look for crystals with absorption coefficients less than 10^{-4}cm^{-1}.

With power densities this high the process is moving into the plasma regime. In a plasma accelerator a longitudinal electric field is established with a traveling wave in an electron plasma. The maximum gradient for a plasma can be found by using Poisson's equation and taking the case where all the plasma electrons are removed at points of rarefaction for the plasma wave [50]. Substituting the plasma frequency $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ into Poisson's equation gives:

$$eE_{max} \sim 0.97\sqrt{n_0} \qquad (13)$$

where E_{max} is the so-called cold wave-breaking field and the force is eV/cm. Here n_0 is the equilibrium electron density. In a gas n_0 could be up to 10^{18}/cm^3 giving rise to a gradient of 1 GV/cm. Clearly this is a significant step forward beyond the earlier schemes.

Chen and Noble appear to have been the first to look at the accelerating process in a channeling crystal in terms of a plasma. With that recognition they could separate the nature of the driver source used to create the plasma from the plasma acceleration mechanism. The plasma could be stimulated by either a laser or a particle beam. For a particle beam there is an additional advantage in channeling since energy loss due to the driver may also be lowered. For a crystal with a plasma density of $n_0 = 10^{22}$ electrons/cm^3 the energy gradient will approach 100 GV/cm. Of course, the required power drive densities will be very high, in the range of 10^{15} to 10^{19} W/cm^2.

Another approach to plasma acceleration was proposed by Tajima and Cavenago [51]. They suggested driving the plasma using Bormann anomalous transmission of x-rays. For Bormann transmission the crystal geometry is arranged so that the x-rays go into a channel at the Bragg angle. They proposed use of 40 keV x-rays and stated that the scheme could give gradients of 1 GV/cm. Tajima and his collaborators [52] have investigated the beam transport in the crystal [53], the x-ray optics, and the crystal survivability. Survivability issues are constrained by the required power densities of 10^{19} W/cm^2 or a power of 10^9 Watts.

As noted earlier, there are several very severe problems with all of these schemes. One is the extremely high power density required. Belotshitskii and Kumakhov appear to have been the first to consider crystal damage in detail. They note that crystal destruction takes place at a power density of 10^{12} W/cm^3 for nanosecond-long pulses. This corresponds to current densities of 10^5 A/cm^2. This is roughly related to the fracture threshold for thermal shock. The exact fate of the crystal for a given energy density will depend on such things as the relaxation time for converting plasmon energy to phonons (a pico-second range process). Clearly many of these schemes rely on power densities well beyond the crystal breaking limit. Of course one can ask if the acceleration process can be completed before the damage occurs. If it does, it might be possible to use a new crystal for each acceleration cycle.

5. EXOTICS

The basic problem with channeling applications is the small phase space of a typical channel. If nature had been kinder there might have been wider channels or higher Z atoms. Indeed nature has provided two of these. A third option is to alter the natural state.

Nature has already provided a range of elements with atomic number higher than silicon. As noted in the materials section, some work is underway to produce better tungsten crystals for channeling applications.

Macro-channeling using hollow nano-scale tubes has been discussed by Kumakhov [54]. In Kumakhov's scheme all surfaces bend. However extremely good surfaces are needed. Carbon nanotubes with apertures in the nanometer range and micron lengths are available [55]. Recently schemes have been developed for making almost millimeter lengths of 20 to 200 nm caliber tubes using bio-membrane techniques [56]. Channeling experiments have already been carried out in highly ordered pyrolytic graphite [57]. There are several potential roadblocks to using hollow-bore nanoscale structures for channeling. These include surface irregularity and channel alignment. These are similar to problems with dislocations and bending beyond the Tsyganov radius. A second type of problem relates to the surface acceptance.

The conditions occurring in a solid state accelerator are an illustration of altering the natural state. What happens to channeling when a crystal is struck by a beam from a powerful laser or particle beam? To answer this it is useful to examine the behavior of the critical angle for axial channeling as the electron screening and the temperature are changed. A useful form for investigating this has been suggested by Andersen [58]:

$$\psi_{1/2} = \frac{\psi_L}{\sqrt{2}}\sqrt{\ln\left(\frac{r_0^2}{u_2^2 \ln 2}\right) + \ln\left(\frac{(Ca_{TF})^2 + u_2^2 \ln 2}{(Ca_{TF})^2 + r_0^2}\right)} \tag{14}$$

where $C = \sqrt{3}$, u_2 is the rms two dimensional lattice vibration amplitude, and r_0 is some channel radius. Removing most of the electrons is equivalent to a large screening length or letting a_{TF} become large. For practical purposes the screening length reaches its limiting values when $a_{TF} = r_0$. For silicon at high temperatures $u_2 = 0.006\sqrt{T}$ where u_2 is in Å and T is in °K. The critical angle behavior as a function of a_{TF} and T are illustrated in Figure 1. Perhaps surprisingly, the changes in the critical angle are not large.

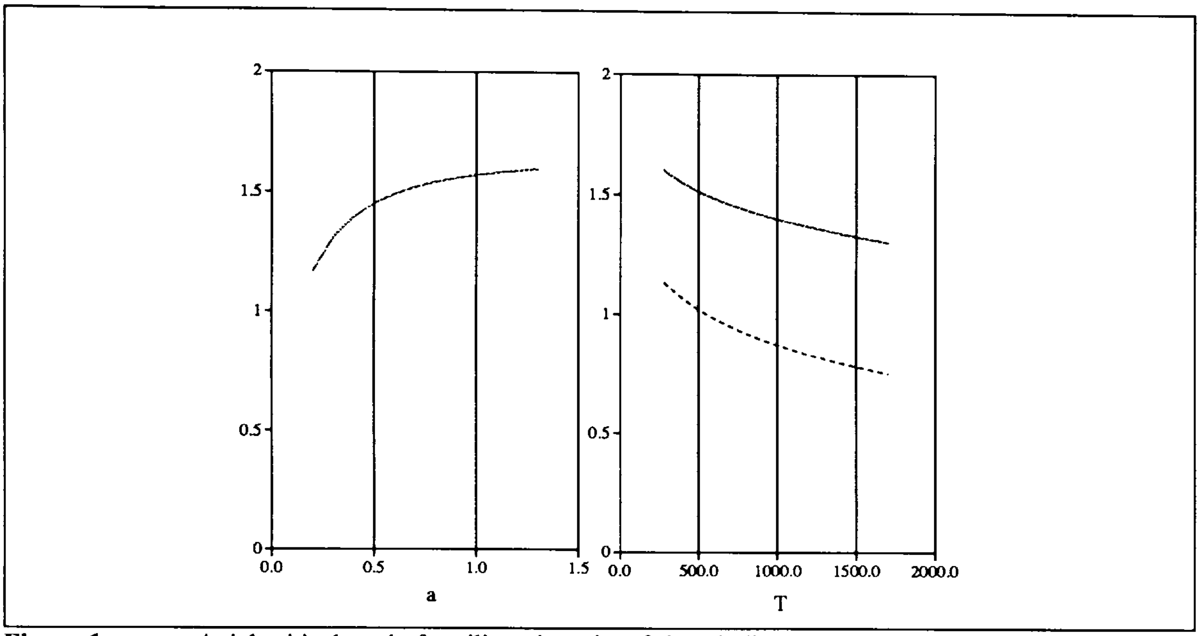

Figure 1 Axial critical angle for silicon in units of the Lindhard angle as a function of a variable screening length and temperature. The solid line for temperature is the unscreened case.

To associate these numbers with the time history of the crystal order it is necessary to understand the evolution of the electron density and the lattice vibrations. How these evolve is a complicated problem. Many of the materials issues have been addressed [59] in connection with laser inertial confinement. In a typical case, a substantial fraction of the electrons might be swept away in much less than a picosecond and the critical angle would grow by 50%. The expanding plasma of ionized electrons might impede the passage of x-rays through the crystal. If the electron plasma was heated too fast the electron density would become too low for some exotic accelerator applications. As the process continued the critical angle would then shrink as ionized electrons generated phonons.

These are the same conditions that naturally prevail for any solid state accelerator. The reasons for considering channeling are beam radiative cooling and the possibility that there may be some channeling gains such as higher effective fields and longer dechanneling lengths. These will be transient effects that will disappear quickly as the crystal vaporizes. Interestingly, beam currents are high enough here that it may be important to consider coherent channeling effects similar to those seen in conventional particle accelerators.

With the advent of "tabletop" terrawatt lasers it may be possible to study channeling dynamically under such conditions. Relatively low energy (MeV regime) channeling back-scattering techniques (RBS) may be satisfactory since one is probably talking about thin crystals. However picosecond channeling RBS studies will require instantaneous currents of many kiloamps. A candidate facility is the Karlsruhe light ion accelerator (KALIF) [60]. Another possibility might be to observe bending of intense multi-GeV beams. Relaxation of the bend due to heating could be a complication. Detecting particles with sub-picosecond time resolution would require innovative tools like Kerr cells. The Fermilab wake-field facility [61] may also offer another venue for tests. At Fermilab a high-powered chirped laser will be used to produce electrons by photo-ionization. This arrangement will serve as the source for a 20 MeV linac. Part of the laser beam can be split off to illuminate a crystal placed in the electron beam. With this arrangement one might hope to study the time evolution or degradation of channeling radiation in the picosecond regime as the crystal was heated by the laser.

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