

Studying and Applying Channeling at Extremely High Bunch Charges

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Abstract

The potentially high plasma densities possible in solids might produce extremely high acceleration gradients. However solid-state plasmas could pose daunting challenges. Crystal channeling has been suggested as a mechanism to ameliorate these problems. A high-density plasma in a crystal lattice could quench the channeling process. There is no experimental or theoretical guidance on channeling for intense charged particle beams. An experiment has been carried out at the Fermilab A0 photoinjector to observe electron channeling radiation at high bunch charges. An electron beam with up to 8 nC per electron bunch was used to investigate the electron-crystal interaction. No evidence was found of quenching of channeling at charge densities two orders of magnitude larger than in earlier experiments. Possible new channeling experiments are discussed for the much higher bunch charge densities and shorter times required to probe channeling breakdown and plasma behavior.

Introduction

For many years crystal channeling researchers have dreamed of using aligned crystals to accelerate charged particles. Robert Hofstadter¹ mused on the limitations of conventional accelerators and speculated on an early version of a channeling accelerator. In his words *"To anyone who has carried out experiments with a large modern accelerator there always comes a moment when he wishes that a powerful spatial compression of his equipment could take place. If only the very large and massive pieces could fit in a small room!"* What Hofstadter imagined was a tabletop accelerator he called **Miniac**. The device would consist of a single crystal driven by an x-ray laser. Channeling would be used to focus the beam. Hofstadter realized the device might be an after-burner to boost a conventional accelerator beam that was already up into the relativistic regime. At the time channeling was a new subject and x-ray lasers were distant dreams.

The limitations of conventional particle accelerators are widely recognized; magnetic fields for circular machines capped at 10 Tesla and RF gradients on the order of 0.5 MeV/cm. With the invention of the laser many explored the possibility of pure laser accelerators. Unfortunately the electric vector for a typical electromagnetic wave points transverse to the direction of propagation and optical frequencies make the construction

of an electromagnetic cavity outside of the reach of conventional technology. Nevertheless a number of ingenious ideas for laser acceleration have been put forward including Palmer's comprehensive 1980 study². In the last several years there has been some real progress on this at Brookhaven³. A large-scale R&D program, LEAP, is now underway at Stanford/SLAC⁴.

A different approach has been to accelerate particles using a plasma wave. Some noteworthy discussions of this include articles by Dawson⁵ and his collaborators as well as the comprehensive review by Esarey et al.⁶ All of these approaches use gas plasmas, not a plasma generated in a solid.

In the last years there has been progress on something that might at first glance be considered solid-state acceleration. Groups from Livermore⁷, Michigan⁸, Rutherford⁹ and LULI¹⁰ have all seen energetic ions and electrons emanating from thin foils struck by extremely powerful picosecond laser pulses. At Livermore they observe "beams" of 10^{13} protons downstream of a foil irradiated with a 1000 TW, 3×10^{20} W/cm² laser pulse. A beam can be focused by curving the foils. The high-energy ions originate from deposits or contaminants on the downstream side of the foil. The accelerating electrostatic field at the downstream surface is produced by ponderomotively accelerated hot electrons generated by the laser pulse. While this is an interesting process it should probably not be considered a solid-state accelerator since the electrostatic field is outside the solid.

In the late 1990s Helen Edwards' group at Fermilab built a prototype photoinjector at A0 to work on development of the Tesla injector¹¹. The accelerator can deliver very large 14 MeV picosecond electron pulses on the order of 10 nanocoulombs or 10^6 A/cm².

The Fermilab A0 photoinjector offered a means to probe in the direction of channeling conditions characteristic of those needed for solid-state acceleration and do observations of channeling under conditions never studied before. The channeling radiation experiment discussed here¹² was designed to initiate this program.

Plasma Wake Field Acceleration

In wake field acceleration a laser or electron beam driver creates a moving wave in a plasma. In turn that wave accelerates a charged particle. Figure 1 illustrates a metaphor for the plasma wake field acceleration process. Notice that the surfer in the figure does not have a rope attaching him to the boat as he would if he was a water skier. In this illustration the driver is a powerful motorboat. The particle, here a surfer, is pushed along by the wave. Phase stability is important. If the surfer drifts too far down the wave he no longer moves forward. He can accelerate for a while by moving up the wave. The plasma wake field acceleration process is very similar to the metaphor.

The gradient in a plasma is $G \approx 0.96\sqrt{n_0}$ where n_0 is the electron density (per cm³) and G is in V/cm. For a good electron plasma in a gas the density might reach

$10^{18}/\text{cm}^2$ and produce a gradient of 1 GV/cm. For a solid the density could be 10,000 times higher corresponding to 100 GV/cm. This is a step in the direction Hofstadter was hoping for.

In the last several years SLAC has run a series of increasingly sophisticated wake field acceleration studies¹³. Typically a 30 GeV electron or positron beam impinges on a meter-length Li plasma produced by an ionizing laser. The head of the beam produces a wakefield. That wake field accelerates the tail to O(100 MeV) depending on conditions. At Fermilab Barov et al.¹⁴ have produced similar results with the A0 photoinjector.

The Advantages and Challenges of Crystal Acceleration

The basic solid-state crystal acceleration paradigm is to excite a plasma wake field in a crystal with a density thousands of times higher than a gas plasma. This possibility has been explored in some detail by Chen and Noble¹⁵. Recent developments in femtosecond laser and electron beam technology make this possibility thinkable. Channeling could be used to reduce energy loss, to focus the particles, and perhaps even cool the beam. But there are big problems. The electron or laser driver beam is so powerful that the crystal may be blown away. In addition there is the classical problem of dechanneling.

To consider a crystal accelerator one must first understand what happens to a crystal exposed to such intense radiation. Chen and Noble¹⁶ have developed sketches of the process that are useful guides. Initially an electronic plasma is excited by so-called tunnel ionization. The electron plasma frequency is

$$\omega_p = (4\pi n_0 e^2 / m_e)^{1/2} \quad (1)$$

The electronic plasma decays via electronic interband transitions with plasma lifetimes in the femtosecond range. That decay to a hot electron gas excites phonons in the lattice. That can lead to crystal disorder, fracture, or vaporization. The ionic plasma lifetime goes as the square root of the ratio of ionic mass divided by the electron mass so that serious lattice damage may occur within 10 to 100 fs. At Livermore¹⁷ hydrodynamic heating is seen to occur in the 1 to 10 ps range. These times are short but not so short that one can discount the possibility of plasma acceleration.

These comments have to be understood in the context of what is required for acceleration and some other observations of materials exposed to intense laser and particle beams. For a plasma gradient of 1 GeV/cm the required laser power density is of order 10^{19} W/cm^2 . Laser crystal destruction occurs for power densities of order 10^{13} W/cm^2 . The lattice is ionized with power fluences of 10^{15} to 10^{16} W/cm^2 . Charge densities of order 10^{16} e/cm^2 are required to get near the acceleration regime. Current densities of 10^{11} A/cm^2 can fracture the crystal. Parenthetically, no evidence of electron beam damage was seen over the course of the A0 channeling radiation experiment. On the other hand several adverse effects were observed in the laser system that powers the

A0 photoinjector. The laser slab ruptured under continuous operation at 10^3 W/cm^3 corresponding to 10^{15} W/cm^3 for 10 fs. There was lens damage at 10^9 W/cm^2 . In principle the laser might be able to operate to deliver 1 Joule to a 10 micron spot in 1 ps or 10^{18} W/cm^2 . This is already in the regime where it could be an interesting driver for a plasma accelerator.

How would channeling be affected as a crystal vaporized? I call this process *dynamic channeling*. As far as I know there is no well-developed theory of dynamic channeling. Andersen¹⁸ has suggested a treatment based on a screening length that increases when the electrons are removed due to ionization. In the Andersen picture the channeling critical angle as a function of temperature and screening length is

$$\Psi_{1/2} = \frac{\Psi_L}{\sqrt{2}} \sqrt{\ln\left(\frac{r_0^2}{u_2^2 \ln 2}\right) + \ln\left(\frac{(\sqrt{3}a_{TF})^2 + u_2^2 \ln 2}{(\sqrt{3}a_{TF})^2 + r_0^2}\right)} \quad (2)$$

where Ψ_L is the Lindhard angle. Here r_0 is some channel radius and u_2 is the rms two-dimensional lattice vibration amplitude equal to $0.006 \sqrt{T}$ at high temp for u_2 in Å and T in °K. Removing most of the electrons is equivalent to a large screening length or letting the Thomas-Fermi screening length, a_{TF} , become large. For practical purposes the screening length reaches its limiting value when $a_{TF} = r_0$. The behavior of the critical angle is shown in Figure 2 as a function of temperature for two different screening lengths. The critical angle for a fixed screening length does drop as the temperature increases but actually increases for larger screening lengths. The point is that the changes with temperature and screening length are not so large. Channeling would seem to survive until the nuclear centers in the lattice have displacements in the Å range, that is, until the crystal ceases to be a crystal. It would be useful to have a well-developed treatment of dynamic channeling as a framework for future studies of channeling under conditions similar to those needed for solid-state acceleration. Lacking a concrete theory, the dotted line in Figure 3 suggests how the channeling radiation yield might diminish as the beam intensity increased to the regime where the crystal is vaporized.

The Fermilab A0 Studies

The Fermilab channeling radiation experiment was undertaken to extend channeling studies toward the solid-state acceleration regime. Channeling radiation was investigated at A0 in part because earlier experiments had looked at this and in part because it was practical to do a channeling radiation experiment at the high bunch charges at A0.

Only one study of the effect of increasing bunch charge on channeling had been undertaken prior to the Fermilab A0 experiment. This was a channeling radiation study at Darmstadt at 5.4 MeV aimed in part at studying the practicality of channeling radiation for medical applications¹⁹. In addition there was a single measurement at Stanford²⁰ at 30 MeV. The Stanford measurement was for a different crystal orientation. The Stanford

value at higher bunch charge was lower than the Darmstadt measurements which appeared to be flat with increasing bunch charge.

As noted earlier the Fermilab photoinjector was able to produce extremely large bunch charges. In addition it was also possible to operate with dark current alone and thereby get a $10^5 - 10^6$ reduction in bunch charge so that the experiment was able to cover a wide dynamic range.

In the A0 experiment electrons moving along a crystal axis or plane produced channeling radiation. The electron beam typically had an emittance of $10 \text{ mm}^* \text{mrad}$ with a 10 ps long bunch. The beam spot size was characteristically 0.5 mm (σ). A spectrometer magnet swept the beam into a Faraday cup and beam dump. An integrating current transformer was also used to monitor the bunch charge. The channeling radiation showered in a calcium tungstate sheet and produced visible photons that were detected by a photosensitive device.

The design of the crystal goniometer was predicated on the extremely tight requirements on both vacuum and the need for a dust-free environment for the photoinjector and the superconducting cavity. In addition a large diameter, thin silicon crystal was used to eliminate background from the crystal holder due to beam halo. It was mounted with the $\langle 100 \rangle$ axis along the beam line. The crystal was aligned by looking at the x-ray signal as a function of the goniometer angles. The experiment consisted of determining the axial and planar yields as a function of bunch charge and dark current.

Because of the extremely high rate it was not possible to count individual particles or photons. Two different detection approaches were used, both employing CaW screens viewed by either a photomultiplier (AberX lite) or a CCD camera (AberX). The photo-detectors were calibrated by placing them in a variable mono-energetic x-ray beam at the Argonne Advanced Photon Source.

For a twelve decade span of bunch charge Figure 3 shows the channeling radiation yield as x-rays/bunch in a 10% band. This unit was used to facilitate comparison to the earlier Darmstadt data. The A0 phototube data are represented by open and filled diamonds obtained for axial channeling from Si with the laser on and with dark current, respectively, and for the AberX detector as indicated by the open triangle for planar channeling. The filled circles result from the earlier Darmstadt measurement of axial channeling in a diamond crystal with electrons of 5.4 MeV and the filled triangle from the Stanford measurement of planar channeling in a Si crystal at 30 MeV. All points have been scaled to $T = 5.4 \text{ MeV}$. Over the 12 decades of the measurements the data trend for the yield per electron is flat.

The Future of High Bunch Charge Channeling Measurements Beyond A0

Two advances are required to move channeling studies fully into the plasma acceleration regime. One is to increase bunch charge per unit area by factors of 10^3 to 10^5 . Part of this can be accomplished by using more focused beams. The second is to use

pulse lengths in the 10 fs regime. This is challenging but there have recently been significant developments in femtosecond laser technology that could help. Higher beam energies might reduce beam size and perhaps also help for channeling studies. However high energy channeling experiments are different and often harder to arrange than the A0 study.

An example of a potential facility for investigating channeling radiation is E164 at the SLAC 30 GeV FFTB facility²¹. This is being used for continuing plasma acceleration studies. By adding a crystal and a high energy gamma ray detector it might be possible to do a channeling radiation study there along the lines of experiments carried out at Serpukhov²² and CERN²³. The relative beam charge at SLAC is less than at A0 but the beam cross section is substantially smaller so that the bunch charge per unit area would be 500 times larger. The potential reach of SLAC E164 relative to A0 is schematically shown in Figure 3 (schematically because the graph is expressed per bunch while the relevant factor is bunch charge per unit area). The 300 femtosecond pulse length at the facility is a step forward but not all the way to the plasma acceleration regime.

A second possibility is to use the 100 TW laser facilities at Livermore to get extremely high beam currents. A 100 fs laser capable of producing a 50 micron spot with a beam power density of 5×10^{18} W/cm² is used at Livermore to generate protons by a pseudo solid state acceleration process in the first foil. The proton beam produces 4 eV plasma conditions in a second foil. Could one do channeling studies with this geometry by replacing the second aluminum foil with a crystal? One possibility might be to try Rutherford back scattering although it is not obvious how the backscattering detector could be incorporated in the geometry. Another possibility might be a blocking experiment. Lattice behavior with time could be studied using pump and probe and streak camera techniques. "Available" petawatt lasers could get up into the 10^{14} protons/bunch regime.

There have also been recent studies in other fields that suggest different paths to follow for investigations of crystal lattices in dynamic situations. An intriguing example is a study of laser melting at Toronto using sub-picosecond electron diffraction²⁴. They use a special 500 fs electron gun to study electron diffraction as a very thin polycrystalline aluminum foil is heated by a laser that is weak by the standards discussed above. The transition from the electronic plasma stage to phonon melting is clearly indicated in the successive Bragg diffraction pictures.

These are three very recent illustrations of potential experimental approaches from a rapidly emerging field studying behavior of solids under dynamic conditions. Many of the possibilities are driven by developments in laser technology. Channeling may have something to offer these studies. Conversely, one might learn interesting things about channeling. And maybe, one may be able to take a step toward solid-state acceleration employing oriented crystals.

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Figure captions

Figure 1 Wake field surfer metaphor for plasma wakefield acceleration (courtesy S. Carrigan).

Figure 2 Axial critical angle for silicon as a function of temperature for two different screening lengths.

Figure 3 Channeling radiation yield (x-rays/bunch in a 10% band) over a twelve-decade span of bunch charge. The present data are represented for the AberX-Lite detector by open and filled diamonds obtained for axial channeling from Si with the laser on and with dark current, respectively, and for the AberX detector as indicated by the open triangle for planar channeling. The filled circles result from an earlier measurement of axial channeling in a diamond crystal with electrons of 5.4 MeV and the filled triangle from planar channeling in a Si crystal at 30 MeV. All points have been scaled to $T = 5.4$ MeV.

Figures

Figure 1



Figure 2

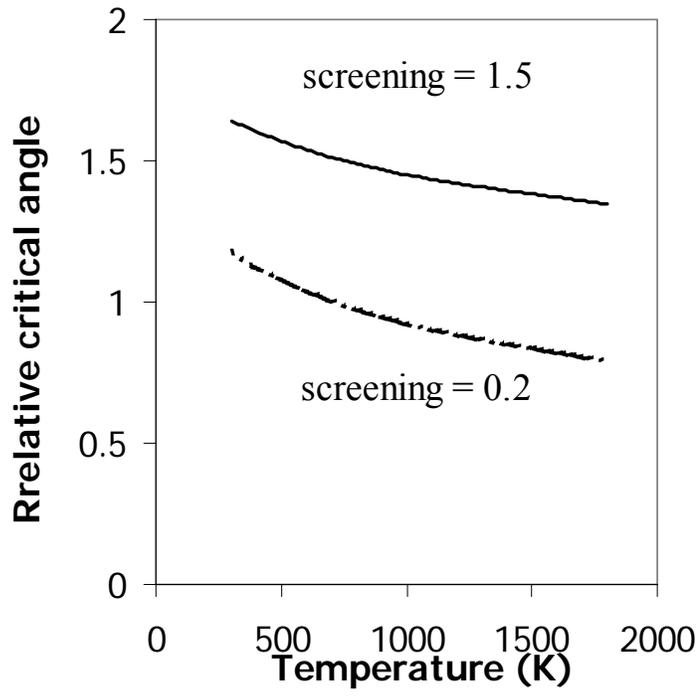
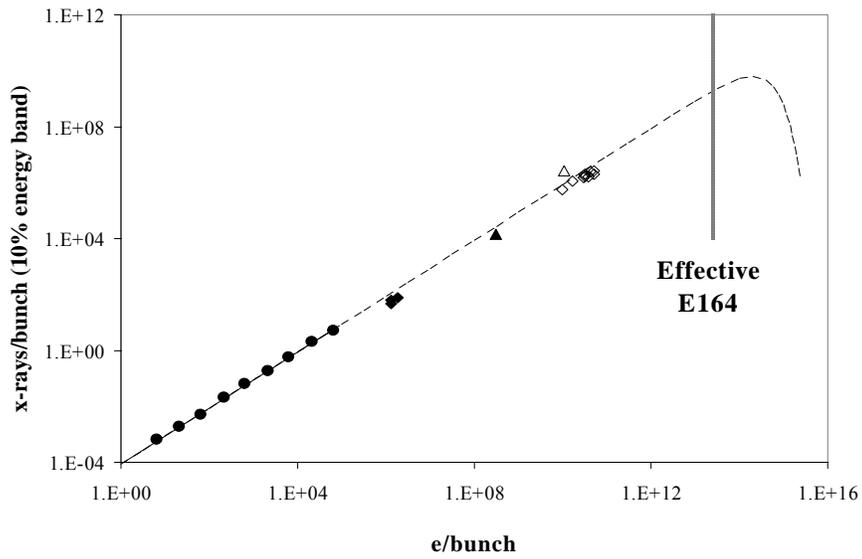


Figure 3



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