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Fundamental channeling questions at ultra relativistic energies

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ABSTRACT

TeV-range bent crystal channeling has interesting advantages for several applications at high energy accelerators. Observations of enhanced deflection over the whole arc of a bent crystal at RHIC and recently at the Tevatron may be due to a process called "volume reflection." More investigations of volume reflection and of the complimentary process, volume capture, are needed. So-called quasimosaic bending processes also deserve additional study. Negative particle channeling may be relevant to channeling collimation for electron machines. Electron and positron channeling and channeling radiation are interwoven so that the impact of channeling radiation on applications needs to be better understood. Beams in the 0.1 to 1 GeV range may be useful for some of these investigations. Finally there has been little or no study of positive and negative muon channeling. The current understanding of these topics and the desirability of further work is reviewed.

Keywords: Channeling, bent crystals, volume reflection, volume capture, muon, RHIC, Tevatron, LHC, radiation damage

1. INTRODUCTION

Consideration of channeling as a tool for multi-hundred GeV particle physics began at Fermilab in 1974 with a discussion of the possibility of using oriented single crystals to investigate the newly discovered J/ψ particle[1]. That interest led to a proposal to study channeling at Fermilab in the multi-hundred GeV regime. The Laboratory administration asked the experimenters to use the Tsyganov-Drickey apparatus that had just been employed to measure the pion form factor. During the experiment Tsyganov had a "once in a lifetime" idea, bent crystal channeling[2]. He returned to Dubna and carried out the first bent crystal channeling experiment at the Dubna synchrophasotron. Since then there have been important programs to investigate bent crystal channeling at Serpukhov, CERN (in concert with Aarhus), Fermilab, and RHIC. The first TeV-scale studies occurred with the E853 extraction experiment in the mid-nineties at the Tevatron.

While the initial Dubna program carried out an extraction study, later experimental programs through most of the eighties shifted to work in secondary beams. Interest in extraction reawakened in part because of significant limitations on conventional extraction at Serpukhov and also because of potential extraction challenges at the future SSC and LHC. The observation of multi-turn extraction at CERN[3] revolutionized the outlook for channeling extraction. Short crystal bend innovations from Serpukhov and LNPI have also enhanced the process. Now in the last few years the discovery of whole-arc bending at RHIC[4] with the recent confirmation at the Tevatron has opened the possibilities for collimation and extraction even further.

There are several factors that will influence the success of crystal collimation. Fundamental channeling topics like scaling from lower energies to higher and the channeling behavior for different particle species such as electrons and even muons will influence the range of applicability. A second part of the collimation challenge is the link between accelerator physics and channeling. The third element is not fundamental at all. This involves technical problems like target heating, radiation damage, and the orientation and fabrication of crystals, benders, and goniometers. R. Assmann[5] has summarized these various challenges as eight questions. Three bullets ask about handling collimation over a large

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range of energies, the details of the crystal deflection process down to the 10^{-5} level, and the sensitivity to beam direction and angular spread. A fourth asks about the impact of the various collimation objects on the accelerator. The last four are the important technical problems.

The next sections of the article discuss whole-arc channeling, negative hadron and e^+/e^- channeling, muon channeling, and technical problems like radiation damage and crystal preparation.

2. WHOLE-ARC CHANNELING

Whole-arc channeling was first observed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and then confirmed at the Fermilab Tevatron. The Fermilab investigation has used the original RHIC goniometer and crystal relocated to the Tevatron E0 straight section. Figure 1 illustrates a goniometer scan using the E0 beam loss monitor LE033C[6]. The rate is proportional to the nuclear interactions in the collimator including the effect of multiple turns. When the crystal channels the beam is kicked away and presumably no longer circulates. However there is also an interesting shoulder over the whole arc of the bend. This is a coherent effect that was observed originally at RHIC. What is it? Biryukov using his channeling simulation code CATCH[7] and the accelerator lattice has done a simulation that shows remarkable agreement with this scan.

In the Tevatron E853 crystal extraction experiment[8] we were not conscious of whole-arc channeling. Normal crystal extraction did not see whole-arc effects. Most of our studies were made using the extracted beam line. This required almost the whole crystal bend for extraction. E853 did have interaction counters, so-called U counters, but they often drifted so they were not trusted. Figure 2 illustrates an artifact that shows something that almost looks like a portion of a whole-arc shoulder. Typically in E853 the scan curve was terminated shortly after the channeling peak was mapped out. Note that the more negative angle is the convex side of the bend, the side associated with the process called volume reflection discussed below.

Whole-arc or coherent bend effects could arise from several different processes including volume reflection and volume capture. Volume reflection was discovered in simulations by Taratin and Vorobiev[9] in the eighties. In essence particles reflect off of planes when they are nearly parallel to a curving plane and are deflected on the order of a critical angle away from the bend. The process will occur over the whole arc of the bend. It can be cumulative for many passes.

Volume capture is another process whereby particles outside a channel in a bent crystal diffuse into the channel. It was first investigated at the Petersburg Nuclear Physics Institute (PNPI) at 1 GeV by Samsonov, Sumbaev, and their colleagues[10]. Volume capture should deflect in the direction of the bend. This diffusion process is an analog of dechanneling where the particles diffuse in to the channel. The process occurs over the whole arc of the bend. Deflections can range up to the whole arc. In their book Biryukov, Chesnokov, and Kotov[11] (BCK) gives this formula for the transition probability to diffuse into the channel:

$$w_s \sim const \frac{R}{(p\beta)^{3/2}} \tag{1}$$

where R is the radius of curvature, p is the particle momentum, and β is the ratio of the velocity v to the speed of light. As the energy goes up, volume channeling goes down. As R gets smaller (tighter bend) it also decreases. BCK have shown that this relation holds true for 70 GeV protons and is characteristically small compared to ordinary bent crystal channeling.

Since the expected acceptance per unit length for volume reflection is $O(\psi_c)$, where ψ_c is the critical angle, the acceptance will go as the critical angle and be proportional to $1/(p\beta)^{1/2}$. The bending radius R does not appear but for a bent crystal ψ_c will be a function of R. As a result volume reflection will diminish more slowly than volume capture as the energy increases. This is why many expect the whole-arc effect seen at RHIC and the Tevatron is due to volume reflection. **In any case it would be useful to understand p, R scaling for the whole-arc process since we are extrapolating to the LHC.**

Other whole-arc or quasi whole-arc possibilities include a crystal miscut or a relaxed bend. A crystal miscut could modulate the effective channeling distribution but would probably not produce a flat shoulder. A relaxed bend would not produce the full angular distributions seen in both the RHIC and Tevatron results. The various possibilities for the whole-arc effect are shown in Table 1.

Effect	Angle dist	Deflection	Magnitude	Comment
Volume reflection	$\Theta_d \sim \psi_c \sim 1/(p\beta)^{1/2}$	Away from bend	Strength same as channeling	Cumulative with beam passes
Volume capture	Up to full bend	Toward bend	$w_s \sim const \dfrac{R}{(p\beta)^{3/2}}$	Small at high energy
Miscut	Lowers deflection	Toward bend	0 to full deflection	
Relaxed bend		Smaller bend		Ruled out by whole arc distribution
Something else				Keep an open mind

Table 1

What should this shoulder be called? Whole-arc or whole-bend channeling gets at the actual effect without positing an explanation. Volume reflection where the particle reflects off a crystal plane may be the correct physical process. In that light it could be named the Vorobiev-Taratin effect. They discovered the process but did not apply it to the accelerator case. Volume capture, the process where a particle suffers a scattering and drops into a channel, seems the less likely explanation at this time. Perhaps it should be called the Fliller shoulder after the graduate student at RHIC who wrote his thesis on the subject. However the recent Tevatron confirmation has also been an important factor in the acceptance of the results so one might also call it the Fliller-Still shoulder. I have suggested calling it the L5 effect. This is whimsical but nearly half of Fliller-Still is composed of the letter L. Once the correct physical process is identified I expect that name will be used. In any case one should keep an open mind until the mechanism is definitively understood in an accelerator environment.

3. NEGATIVE PARTICLE AND ELECTRON/POSITRON CHANNELING

The LHC collides only proton beams so that crystal collimation as demonstrated at the Tevatron will work for both circulating beams. But could one use crystal collimation to collimate antiproton beams at the Tevatron? Indeed could it be used to collimate positrons at the future International Linear Collider (ILC)? Would it even work for electrons? For electrons and positrons channeling radiation may be an important consideration. Crystals have been suggested as devices that could be used in very forward experiments like TOTEM[12] at the LHC. Could those devices work on negative particles? Futuristic possibilities like neutrino factories based on muon storage rings and even muon colliders have been discussed. Muon channeling is discussed in the next section

In thinking about the possibility of negative particle deflection in the early eighties I discounted it because I thought in terms of discrete angular deflections in the spirit of an external beam. The situation is different for collimation where the important thing is to give the particles a kick, any kick, provided it is more than multiple scattering. Multi-pass channeling also helps the collimation process. High energy may also help.

There has been little study of negative hadron deflection using bent crystals. A significant problem is that negative particles in a channel move in a region of high ion density so that dechanneling is expected to be much faster. Two decades ago I estimated that negative hadronic dechanneling was more than an order of magnitude larger than dechanneling for positive particles. That is to say, the dechanneling length would be much smaller. At the TeV scale this might not matter so much for short collimation devices.

There does not appear to be much experimental information on electron and positron dechanneling. Much of the information is quite old. There has also not been a great deal of theoretical work in the subject. Most of that work is also several decades old and addresses relatively low energies. One exception is the recent study by Koral et al.[13] discussing crystal undulators.

Table 2 lists some theoretical and experimental values for axial and planar dechanneling lengths adjusted to 1 GeV assuming a linear scaling with energy. A linear extrapolation may not be appropriate. Values are given in microns (µm). Some of the values are 1/e lengths while others are half lengths. In practice the incident beam angular distribution is an important factor in determining the length for both theoretical and experimental cases. Most of the data was taken below 1 GeV. There are significant statistical uncertainties surrounding these numbers.

Process	e^+ dechanneling (µm)	e^- dechanneling (µm)	Energy MeV	Comment	Author
Planar theory	500		1000	Si(110), ½	Beloshitsky and Trikalinos[14]
	700	130 quasi, 13 pure	1000	Si(110), 1/e	Beloshitsky and Komarov[15]
Planar experiment	1100 (60 for occupation length)	660 (36)	54	Si(110), 1/e	Livermore[16]
		88 (31)	350	Si(110), 1/e	Komaki et al.[17]
		23 (28)	1200	Si(110), 1/e	Adejshvili et al.[18]
Axial theory		13	1000	Si<111>, ?	Muralev[19]
		18		Si<111>, 1/2	Taratin and Vorobiev[20]
Axial experiment		32 (39)	1200	Si<111>, 1/e	Adejshvili et al.

Table 2

It would seem that more information on electron and positron dechanneling at all energies including sub GeV cases would be useful. Theoretical work extending the reach to at least the 200 GeV regime would also be helpful.

There has been little study of negative bending. Negative bending might be difficult to observe because of the expected short dechanneling lengths. CERN experiments saw only small deflections of the order of the critical angle for axial bending[21]. Schiott's simulations[22] fitted the experiments.

Some time ago Taratin and Vorobiev simulated negative hadron bending. More recently Greenenko and Shul'ga[23] studied negative deflection with a simulation program. For axial channeling at 400 GeV they saw deflections at the same scale as the Schiott simulation. For 100 GeV hadrons bent 0.3 mrad in a 3 cm crystal they found that the negative deflection was of the same order as the positive case but very diffuse!

What would negative dechanneling experiments look like? D. Still[24] has suggested that it might be possible to study antiproton crystal collimation in the Tevatron by redoing the proton and antiproton helices locally at E0 in the vicinity of the existing goniometer. An alternate approach might be to remove the proton store so that only antiprotons would be circulating in the accelerator. Both approaches require serious accelerator setups. A nearby collimator and detector would be needed in the antiproton downstream direction.

With innovative short bends it might be possible to use bending to study electron dechanneling. This is a regime where GeV scale machines could contribute. Note also that information on electron/positron dechanneling below 1 GeV down to 10 – 20 MeV is not completely consistent. New information is desirable in this regime.

A recent proposal[25] to study beam handling with channeling at the 1.2 GeV Advanced Test Facility (ATF) at KEK in Japan will give a significant opportunity to study electron dechanneling and bending. ATF can provide a very low emittance beam so that the angular divergence is much less than the critical angle. It will be very interesting to look at electron channeling deflections with this system

To recapitulate, if crystal collimation becomes important for something like an electron-positron collider more information will be needed on negative channeling including negative bending! This will include the need for data and theories on negative dechanneling lengths.

4. MUON CHANNELING

Muon channeling is potentially interesting for collimation in a futuristic muon collider or neutrino factory[26]. One challenge for channeling collimation in muon storage rings is the relatively large angular distribution for the pion decay to a muon. This results in a requirement for large aperture storage rings. This could be a constraint for using crystal collimation, particularly at low energy because the critical angle is relatively small compared to the decay angular distribution.

There is little muon channeling experimental data. Most of the information is from low energy pion implantation experiments[27].

As far as I can determine there have been no theoretical studies of muon channeling. As is the case for any particle species the negative particles travel in regions of high nuclear density so that the dechanneling lengths should be shorter and the radiation cross sections higher. On the other hand the critical energy for muons in silicon is 470 GeV so that the impact of radiation processes on channeling will be very much less. For example the muon bremsstrahlung cross section is

$$\sigma_\mu = \sigma_e \left(\frac{m_e}{m_\mu} \right)^2 \qquad (2)$$

where σ_e is the electron bremsstrahlung cross section and m_e and m_μ are the masses of the electron and the muon. As a result there will be much less bremsstrahlung per unit length for muons than for electrons.

Two elements are needed to carry out a muon channeling experiment. One is a muon detector. The other is a beam of muons. Particle identification of a muon uses a hadron absorber in front of the detector. This absorber is typically eight to ten nuclear interaction lengths thick or 1.5 m of iron. Muon beams are tertiary beams. The beam is produced in a sequence where protons striking a target make pions and the pions decay into muons. Each step in this chain reduces the energy of the particle species. For example for 450 GeV protons the average pion energy might be 50 GeV and the muon energies would be less than 25 GeV. The yield of higher energy muons decreases rapidly. On the other hand channeling experiments typically do not require intense beams. The pion mean life is 26 ns so that a long decay space is needed to produce a robust muon fraction. Nevertheless a typical pion beam will have some muon contamination.

Muon channeling collimation is an exotic possibility connected with muon colliders and neutrino factories far in the future. Still it would be interesting to gain more insights into muon channeling. Could investigations be carried out at CERN? Muon detection would be straight-forward. Increasing the muon fractions in readily available beams would be the challenge.

5. RADIATION DAMAGE AND CRYSTAL PREPARATION AND MONITORING

Using a channeling crystal in a high intensity beam presents several challenges. The crystal itself can have a variety of problems including defects such as dislocations and fabrication flaws. Orientation is difficult. The high flux beam can introduce defects and physically damage the crystal. As noted by Assmann, information on crystal survivability with high flux would be useful. For example, it would be helpful to have a theory of channeling survivability.

By now there is a great deal of experience with crystals in accelerator beams. They survive well and sustain serious heat loads without significant problems (up to 150 degrees and 1 W in a bent crystal at IHEP[28]). **CERN**[29] saw only a 25% degradation of bending efficiency for an exposure of $2*10^{20}$p/cm^2. The E853 crystal was in the Tevatron halo for about 70 hours with no noticeable effect. Some years ago our Fermilab group exposed a crystal in the BNL neutrino beam[30] (strictly the proton beam that made the neutrinos). That produced a heroic fluence of $4*10^{20}$ protons/cm^2. After waiting for a year of so for the crystal to cool we looked at it with the SUNY-Albany Dynamitron. The channeling minimum yield went from 2 to 4%. The defects may have been from induced dislocations. So, yes, crystals can be radiation damaged as is shown graphically in the picture of the crystal from the BNL exposure in Figure 3.

There are questions concerning radiation damage that deserve more investigation. Are there effects that scale with energy? How do they scale to 7 TeV? Are there ways to control damage, perhaps with annealing? Might some crystals like diamonds be better than silicon? What types of defects are produced? Could one make a self-monitoring crystal with a deposited fuse film that would indicate a break or even use the semiconductor properties to monitor dislocation or interstitial defect build-up? How does temperature affect the impact of radiation damage?

An intense beam through a crystal could blow away the electrons in less than a picosecond. This would act like a larger screening length. I call channeling under these conditions "dynamic channeling". One could build a model of channeling under these circumstances by discussing the plasma processes at work during the various stages of vaporization[31]. Alternatively, Andersen[32] 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

$$\psi_{1/2} = \frac{\psi_L}{\sqrt{2}} \sqrt{\ln\left(\frac{r_0^2}{u_2^2 \ln 2}\right) + \ln\left(\frac{\left(\sqrt{3}a_{TF}\right)^2 + u_2^2 \ln 2}{\left(\sqrt{3}a_{TF}\right)^2 + r_0^2}\right)} \tag{3}$$

where ψ_L is the Lindhard angle, 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 ºK. 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 plot in Figure 4 shows the relative critical angle as the temperature changes for two different screening lengths. The point is that as the temperature increases the critical angle drops and channeling is throttled. However, this happens relatively slowly.

We carried out a channeling radiation experiment[33] at the Fermilab photoinjector to see if we could observe any change in channeling radiation as electron bunch charge increased. Combined with lower bunch charge measurements the yield per electron was constant over more than ten decades up to a bunch charge of more than 10^{11}/bunch. This was not unexpected in light of the models described above. A drop in yield might start to occur for bunch charges 10^5 – 10^6 larger.

While crystal preparation, characterization, bending, and the possibility of alternate materials may not involve fundamental channeling issues these areas are still very important to progress in collimation with channeling. Figure 5 illustrates the challenging process of preparing and using a crystal in a channeling application. Each step demands special skills and equipment. In the past some of these steps have almost seemed to be separated by windowless walls. The final people in the chain, the end users, may be confused about the origin and quality of the crystal, the orientation and bend angle, even the deflection direction of the bend as the crystals become ever shorter. People working on the LHC channeling collimation challenge such as Ivanov at LNPI, Chesnokov from IHEP, Guidi and his colleagues at Ferrara, Vomiero and others at Legnaro, Taratin and associates from Dubna, have made great progress in this area.

Bad things can happen to ordinary collimators in an accelerator. Recently at the Tevatron a groove was etched into a collimator when the beam struck it as a result of a magnet system quench. Bad things can also happen to operating crystals. The bend can relax. The crystal can break or be degraded by radiation damage. In view of this class of problems it is useful to consider ways to monitor the integrity of operating crystals. Figure 6 schematically illustrates a possible self-monitoring crystal. It might be possible to monitor the bend angle by measuring the capacitance of a flat surface relative to the bent surface of the crystal. A break could be detected using a plated-on fuse strip. Finally leakage current on an implanted diode could be used to monitor radiation damage. Mokhov[34] has noted that electronic damage occurs for exposures thousands of times lower than radiation damage levels that destroy channeling. One possible way to circumvent this would be to implant the diode several σ away from the beam hot spot. A practical self monitoring system would undoubtedly be much different than this schematic picture. Nevertheless it is worth investigating whether some sort of monitoring could be carried out.

6. SUMMARY

Crystal collimation has recently been successfully demonstrated at the Tevatron. RHIC led the way to this demonstration with the first observation of whole-arc bending. Many argue the whole-arc effect is most likely due to volume reflection. At the Tevatron there is still a puzzle about the magnitude of the apparent deflection. That issue will hopefully be resolved by further Tevatron measurements in the near future. Additional improvements will also be added to the Tevatron system soon.

For channeling collimation and extraction it is important to fully understand the nature of whole-arc bending. This will determine how the process scales up to the 7 TeV energy at the LHC. For potential applications like electron and muon collimation as well as LHC forward experiments it would help to better understand negative particle channeling and bending as well as channeling of electrons, positrons, and muons. For electrons and positrons studies in the regime below 1 GeV could be helpful. Practical subjects like radiation damage and radiation damage extrapolation to 7 GeV are also important.

All in all channeling collimation has opened a vigorous new and very exciting field for investigation in the venerable subject of channeling!

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FIGURES

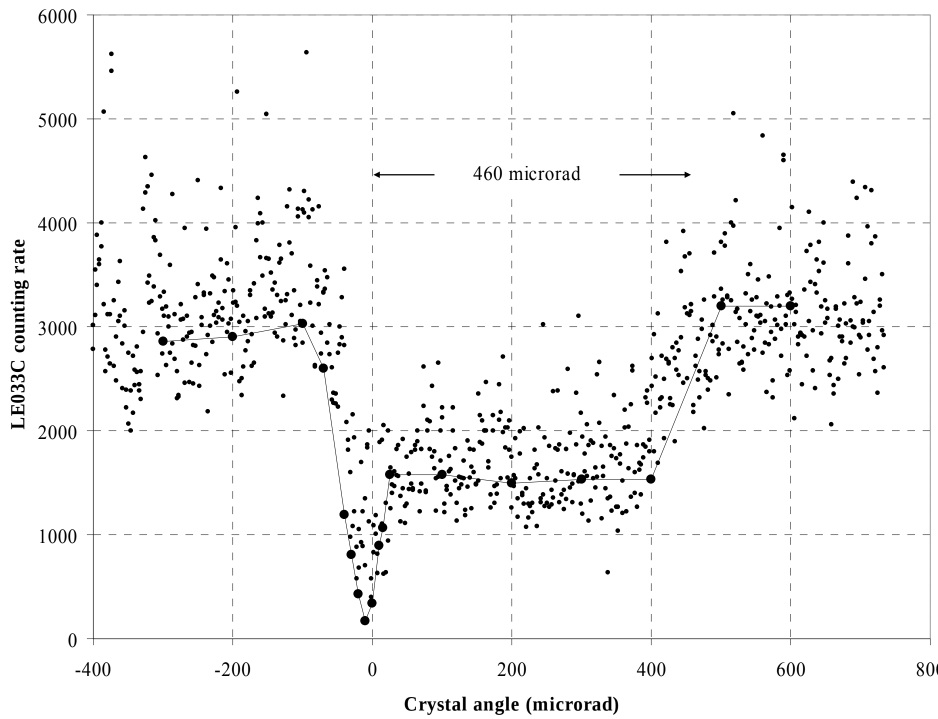

Figure 1: Whole-arc effect at the Tevatron. The large dots are the results from the Biryukov simulation.

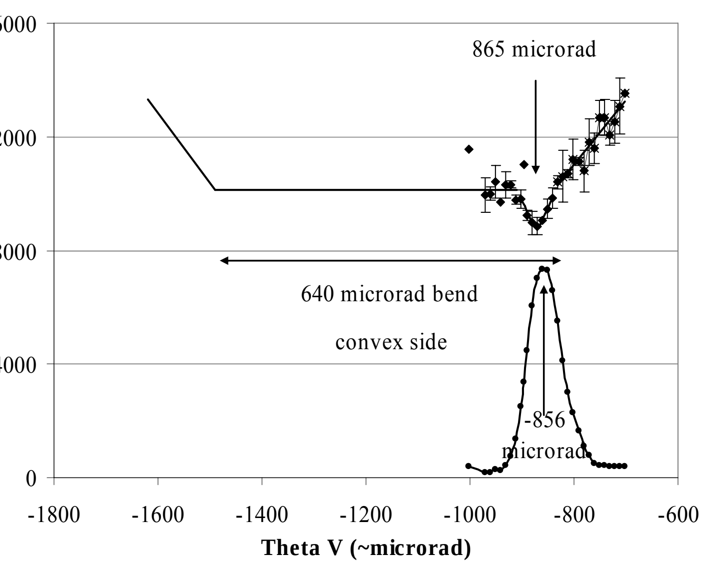

Figure 2: Possible volume effect in E853 at the Tevatron.

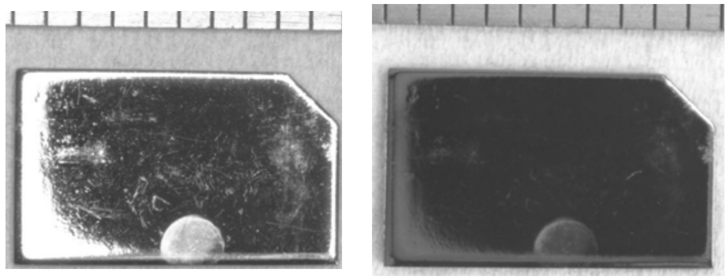

Figure 3: Silicon radiation damage in BNL exposure (scale 1/16 in/div).

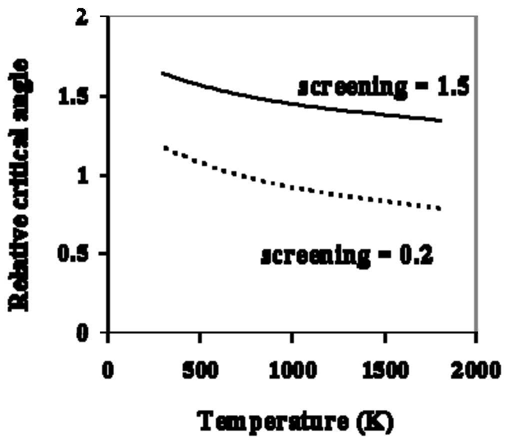

Figure 4: Critical angle as the temperature changes.

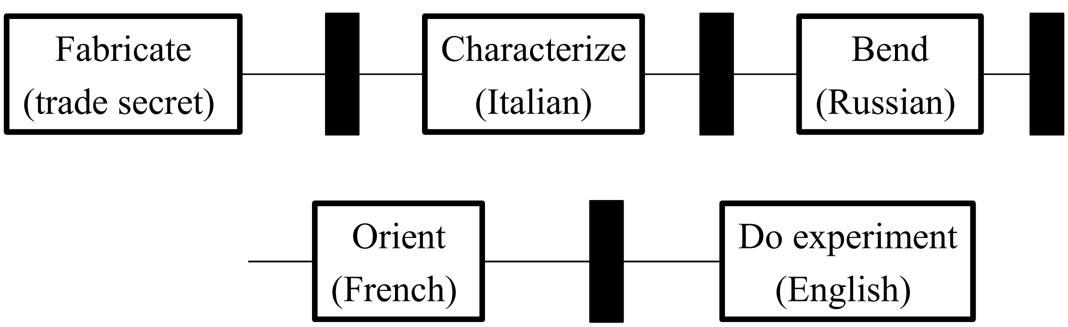

Figure 5: Crystal preparation and use sequence in a channeling experiment.

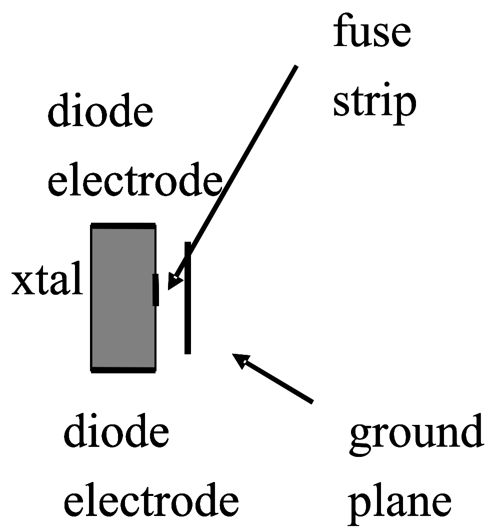

Figure 6: A self-monitoring crystal.