Fermi National Accelerator Laboratory

FERMILAB-Conf-81/50-EXP
7135.660

POSSIBLE APPLICATIONS OF THE STEERING OF CHARGED PARTICLES BY BENT SINGLE CRYSTALS*

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July 1981

*Submitted to the IXth International Conference on Atomic Collisions in Solids, Lyon, France, July 6-10, 1981

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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ABSTRACT

This article reviews some aspects of the steering of charged particles using channeling in bent crystals. Crystal angular and spatial acceptance, deflection, dechanneling, and radiation damage are discussed. Examples of possible bent crystal applications are presented including extraction, beam transport, focusing, the possibility of charm particle separated beams, and magnetic moment determination.

What would happen to a particle in a channeled trajectory if the crystal through which it moves is bent? In 1976 Tsyganov[1] reviewed this question. Bending the crystal is equivalent to introducing a rising centrifugal potential, thereby lowering one side of the channeling potential well and raising the other. In effect, the critical angle diminishes and the dechanneling length shortens. Tsyganov estimated the critical radius of bending (Carrigan[2] calls this the Tsyganov radius) to be

$$R_T = \frac{E}{eE_c},$$

where E is the total energy of the particle and E_c is the interatomic electrical field intensity at the 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. Typical values are given in Table I for 100 GeV/c particles. The planar critical angle at 8.4 GeV for the (111) plane in silicon is about 45 microradians, the critical radius is equal to 2 cm.

This critical radius can be related to an equivalent magnetic field for a relativistic particle by noting that the radius of curvature of a particle in a magnetic field is $R = p/.03B$ (where $E \simeq p$ (in GeV/c), B is in kilogauss, and R in meters). The equivalent magnetic field for the (110) plane in tungsten is 160 megagauss.

Tsyganov and his collaborators in a joint USSR-USA collaboration have studied channeling in bent crystals in an experiment at Dubna[3]. The experiments were performed in an 8.4 GeV proton beam using thin silicon crystals.

As a crystal was bent the channeled fraction of the beam followed the direction of the downstream end of the crystal. The crystals were bent up to 26 milliradians. Eventually the bending program was limited when a crystal broke at a bending angle slightly greater than 26 milliradians. This was equivalent to a bending radius of 38 centimeters, far larger than the critical radius. Experiments are underway at Fermilab to observe this process nearer the critical radius.

In the Dubna experiment there is relatively little dechanneling when the silicon crystal is not bent. Secondly, differential dechanneling can be seen as the crystal is bent. There appears to be little, if any, increase in dechanneling as the crystal is bent.

Deflection of a beam of charged particles using channeling in a bent crystal is a distinctly different process than bending with a magnet. Up to some momentum related to the critical radius a channeled particle near the plane direction should be deflected independent of its momentum. The lower momenta particles will be lost more rapidly than the higher momenta ones since their dechanneling length will be shorter. At high momenta near the critical radius, more divergent particles will be lost. Channeling with a bent crystal, then, is a wide momentum band pass method of deflecting charged particles. This could be a distinct advantage for beam systems that require the deflection of a large range of momenta. On the other hand the same feature means that such a system would have no momentum selection capability.

There is as yet no information on the behavior of negative particles in a bent crystal. No measurements were made on negative particles in the Dubna run. It is distinctly possible that there would be no deflection of negative particles by a bent crystal.

FACTORS AFFECTING CHARGED PARTICLE BENDING WITH SINGLE CRYSTALS

Materials:

Every facet of the channeling phenomenon is affected by the choice of the single crystal. The critical angle, dechanneling length, Young's modulus, susceptibility to radiation damage, melting point, and temperature effects related to lattice vibrations are all sensitive to this choice.

It appears that a high Z material is quite desirable from any standpoint. For example, tungsten has a high melting point, relatively small lattice vibrations, and a large critical angle. Tungsten crystals may be the ideal crystals for high energy applications.

Angular Acceptance

The angular acceptance of a channel in one angular direction in a single crystal is determined by the critical angle, that is

$$\theta_a \alpha \psi_c = K/\sqrt{p} \ ,$$

where K is determined by the crystal parameters. The angular acceptance parallel to a plane is infinite. For applications the beam angular divergence would be arranged to be small in the plane of bending and large in the crystal planes. A typical accelerator half angular divergence at extraction is 20 microradians, while the angular divergence of a typical secondary beam is 250 microradians at 400 GeV. The critical planar channeling angle in the (110) plane of tungsten is estimated to be seventeen micoradians at 400 GeV.

Spatial Acceptance

The spatial acceptance of a crystal depends on its transverse dimensions. The amount of bending will also depend on how thick the crystal is in the bending direction. The spatial acceptance will be equal to the height times the thickness in the bending direction.

The maximum elastic deflection of a crystal of length L and thickness t supported at three points is

$$y = \frac{S_m L^2}{6E_y t},$$

where S_m is the maximum stress and E_y is Young's modulus. The maximum deflection can be linked to a minimum radius of curvature by noting that $y = L^2/8R$. The minimum radius of curvature is then

$$R = \frac{3}{4} \frac{E_y t}{S_m}.$$

Clearly the minimum radius is directly related to thickness.

For characteristic silicon values the minimum bending radius is 90 cm for a thickness of 1 mm, quite close to the value of 76 cm found by Tsyganov from observation for the (111) plane.

Deflection:

Tsyganov derives a critical bending radius that is proportional to the momentum at high energies. At 400 GeV/c for the (111) plane in silicon, the Tsyganov radius is 90 cm. From the result of the Dubna experiment it should be possible to bend a crystal 2 cm long and 1 mm thick in the direction of bending on a radius of 90 cm to give a bending angle of 22 mrad. The effective bending power of the crystal corresponds to an extraordinary 15 megagauss magnetic field.

Dechanneling:

The basic dechanneling process has been studied for the axial case by Bonderup et al.[4]. These diffusion lengths go as the energy of the particle so that dechanneling lengths increase with energy. Table I gives these lengths for the <110> axis in silicon, germanium, and tungsten at room temperature.

The phenomenological length for particles to scatter to three times the critical angle measured in a recent Fermilab experiment[5] at 100 GeV along the <110> axis is 13.5 cm. This is approximately twice the nuclear diffusion length at liquid nitrogen temperature calculated from the Bonderup et al. formula. Particles, then, are retained near channels for lengths on the order of, but somewhat longer than, the Bonderup et al. diffusion lengths. Based on this, it seems reasonable to consider the use of crystals up to tens of cm long at multihundred GeV energies.

Crystal Integrity and Radiation Damage:

For bent crystals to serve a useful role in manipulating charged particle beams they must stand up under bending and the induced radiation. The radius used at 8 GeV is approaching the critical radius at 250 GeV. Thus for multihundred GeV experiments it is clear that the introduction of dislocations from bending probably constitutes no problem.

Radiation damage studies of crystals indicate that a dose of 10^{17} protons/cm^2 on a randomly oriented single crystal causes significant damage. An oriented crystal may take higher doses. Annealing may reduce radiation damage.

For comparison, typical beam intensities at high energy accelerators average 10^{12} - 10^{13} particles/sec in extracted beams and 10^6 to 10^9/sec in secondary beams. It seems possible to expose crystals to significant beams and still have them behave usefully.

POSSIBLE APPLICATIONS

Extraction - Bent crystals could provide essentially zero thickness septa for deflecting particles out of accelerators. Crystal bending angles are more than sufficient. Angular acceptance as set by the critical angle matches extraction emittances. Spatial acceptance is satisfactory. Dechanneling losses for such a septum are quite comparable to losses on an electrostatic or magnetic septum. Radiation damage is a significant factor but may not be insurmountable.

Secondary Beam Bending - Near a production target or at a focus crystal size is well matched to beam size. Laminates could also be used to increase the thickness. Angular acceptance is about one tenth of a typical focusing beam emittance. This could be ameliorated by using beam parallel sections but laminates might be necessary.

Use of a crystal septum in the M4 beam at Fermilab has recently been considered by A. Menzioni and J. Elias[6] to deflect high energy, forward produced particles down an existing eight milliradian beam line.

Beam Focusing - Properly sliced single crystals as shown in Figure 1 could give focusing with little loss of aperture. Focusing in two dimensions may be possible by using two such elements.

"Separated" Beams for Short Lived Particles - Lifetimes of charm particles are so short that they move less than 1 cm even at high energies. With crystal bending it should be possible to deflect charm particles several hundred milliradians, well out of the forward production cone. This could give a substantially enriched sample of charm particles if the long lived particles in the same channel continue further around the bend (see Figure

2). Angular acceptance is on the order of 1% of the production cone. At high energy charm particle production is reasonably copious. The problem is more in separating particles, that is to say enrichment is important.

Blocking may limit the application of this process. Investigations of blocking at high energy, with and without bending, are needed.

Charm Particle Magnetic Moment Measurement - L. Pondrom[7] has noted that the electric field of a crystal transforms into a magnetic field in the rest frame of a moving particle. The particle spin will precess around the magnetic vector. For a polarized process it is possible to measure the precession in the same way that it has been done for strange particles. Effective fields in bent crystals are sufficient to precess a magnetic moment several radians in 1 cm.

References

1. E.N. Tsyganov, Fermilab TM-682, TM-684, Batavia, 1976.

2. R.A. Carrigan, Jr., Fermilab 80/45-EXP, Batavia (1980). This note contains an expanded presentation of many of the topics covered in the present article.

3. A.F. Elishev, et al., Physics Letters 88B, 387 (1979).

4. E. Bonderup, H. Esbensen, J.U. Anderson, and H.E. Shiøtt, Rad. Ef. 12, 261 (1972).

5. R.A. Carrigan, Jr. et al., Nucl. Phys. B163, 1 (1980).

6. A. Menscione and J. Elias, private communication.

7. L. Pondrom, private communication.

TABLE I

Some Channeling Properties for 100 GeV Particles

	Silicon	Germanium	Tungsten
Z	14	32	74
A	28.09	72.59	183.85
ρ	2.35	5.33	19.3
Axial Critical Angle (microradian) <110>	46	68	138
Planar Critical Angle (microradian) (110)	16	20	34
Minimum Elastic Bending Radius (1 mm bar, cm, energy independent)	76 cm	∿76 cm	94 cm* (est.)
Critical Field ((110), v/cm)	0.61×10^{10}	1.28×10^{10}	4.73×10^{10}
Tsyganov Radius (planar, (110), cm)	16.3	7.8	2.1
Equivalent Magnetic Field (Megagauss, (110), plane)	20	43	160
Nuclear Diffusion Length (axial, <110>, cm) (room temperature)	10.3	2.2	1.7
Electronic Diffusion Length (axial, <110>, cm)	6.44	7.7	10.8

*Tungsten could probably be bent to a smaller radius if dislocations are introduced.

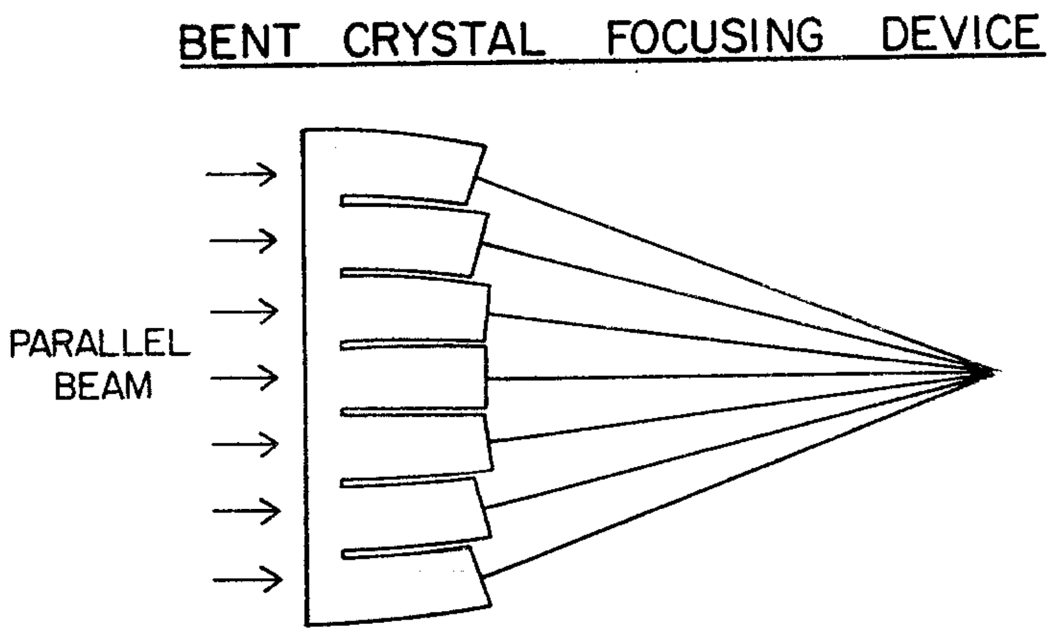

Fig. 1. Focusing element created using sliced and compressed single crystal to produce differential bends.

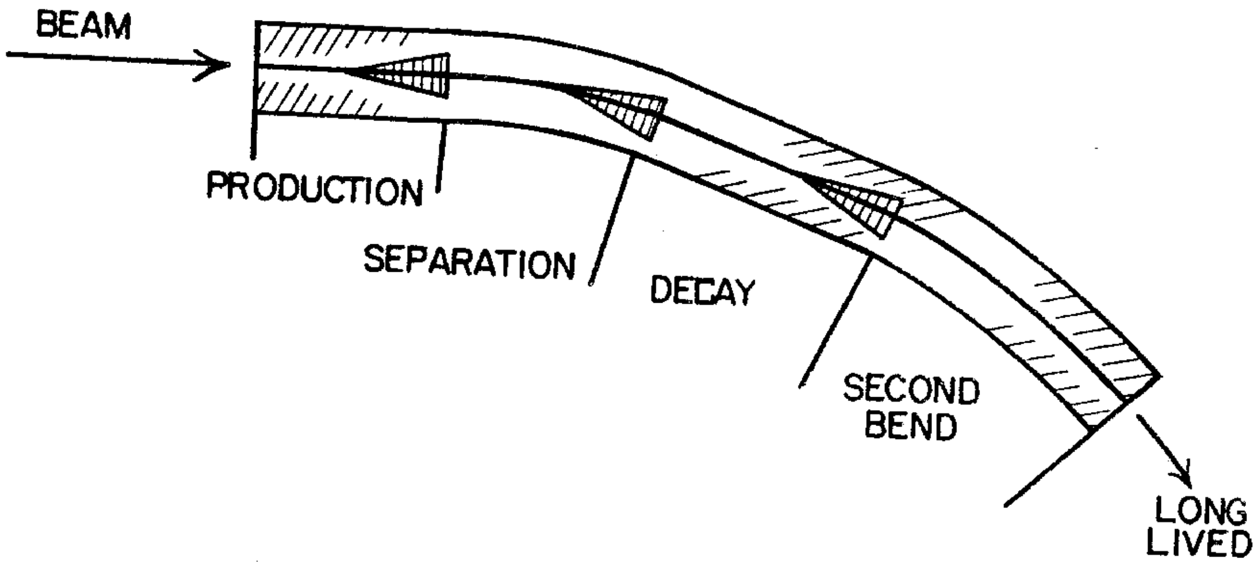

Fig. 2. Proposed "separated" charm particle beam. All particles in critical angle are bent. Charm particles decay in the straight region. Long-lived particles continue around bend.