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Beam Extraction from TeV Accelerators Using Channeling in Bent Crystals *

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ABSTRACT

Bent crystal channeling offers an interesting alternative for beam extraction from trans-GeV accelerators. Conventional extraction employs resonant beam blow-up coupled with electromagnetic beam deflecting channels. It is limited by the length of the available accelerator straight section. Channeling crystals require much less space. A five-step approach to applying crystal extraction in the Superconducting Super Collider (SSC) is discussed. Two steps, extraction from the 8 GeV Dubna Synchrophasotron and the 76 GeV Serpukhov accelerator, have occurred. The next possibility is extraction from a multi-hundred GeV superconducting accelerator. In the nineties the program could continue at UNK (3 TeV) and culminate at the 20 TeV SSC.

The possibilities and limitations of crystal extraction are reviewed. More information is needed on dechanneling in bent crystals including the effects of dislocations at TeV energies. Long, "dislocation-free" crystals are required. A more thorough understanding of the theory of crystal extraction is also desirable.

1. Accelerator extraction

High energy accelerators operate in two modes; with extracted beam to fixed targets and colliding beam configurations like the planned SSC that produce high effective collision energies. SSC plans include no serious technique for extraction. Nevertheless, even relatively weak extracted beams find uses for testing and producing secondary beams.

Accelerator extraction proceeds in several steps[1]. In the first stage slow resonant beam blow-up expands the beam. On its last turn a circulating particle jumps several centimeters into an electrostatic septum formed by a plane of thin (0.05 mm diameter) wires at high voltage. Much of the beam that strikes the wires scatters and is lost. Typical septa are 3-4 m long and impart a 0.04 GeV/c kick, equivalent to an angle of 40 μrad at 1 TeV. Since this is small, a set of kicker magnets follows the electrostatic septum. The incorporation of long straight sections in accelerators has made this extraction process more tractable.

Like electromagnetic septa, bent single crystals aligned for channeling can also be used to extract beam from accelerators. The first suggestion of this possibility is evidently due to Koshkarev[2]. The major advantage of a crystal is that it can deflect the beam through a much larger angle, between 1,000 and 10,000 as large for the same length of septum. Because the channeling critical angle is small, the transmitted beam divergence is low. The penalty is that the crystal acceptance is small, also down by a factor of 1,000 to 10,000[3]. For extraction some of these acceptance considerations are not so relevant.

Crystal extraction was first demonstrated in the mid-eighties at the 8 GeV Dubna Synchrophasotron[4]. The Dubna group used an 11 mm long silicon crystal bent through an angle of 35 mrad. The crystal transmission was 10^{-4}, limited by the area of the crystal transverse to the beam.

In 1989 beam was extracted from the 76 GeV Serpukhov accelerator using a 7 cm long single crystal bent through 80 mrad[5]. Extraction at Serpukhov is challenging because the machine was designed before long straight sections were incorporated in accelerators. The beam must be deflected 80 mrad to clear the magnet lattice. The crystal was cut with a novel rhomboid shape. This avoided the need to precisely align the crystal plane with the beam since different parts of the transverse face of the crystal had different tangents. However the result was less beam was transmitted. The extracted beam intensity was $5*10^{6}$/s. No information is available on the transmission efficiency.

Extraction limitations appear once more at the SSC for several reasons. First, the accelerator is deep under ground making extracted beam manipulation difficult. Second, most of the straight sections are assigned as collision regions or to utility functions like abort systems. Several studies have reviewed the possibility of using crystal extraction to circumvent these complications[6]. Although important decisions about the SSC lattice are now being made, it seems unlikely the specifics of crystal extraction would affect them. In any case the possibility of practical SSC extraction activities is many years away.

Based on that fact an adiabatic approach to SSC crystal extraction seems appropriate. Two steps along the way have already occurred, extraction at **8 GeV at Dubna** and **76 GeV at Serpukhov**. The next logical step is extraction at a multi-hundred GeV machine like the **Fermilab Tevatron** (**800-900 GeV**). A test on the superconducting Tevatron would confront the important problem of extraction beam losses possibly quenching superconducting magnets. The forth step would be a test on the **3 TeV UNK accelerator** under construction at Serpukhov. The process would culminate in the fifth step at the **20 TeV SSC.**

In spite of the progress so far, there has still been no comprehensive investigation of the theory of bent crystal extraction.

2. Channeling factors

Several crystal characteristics affect the use of channeling for accelerator extraction. Dechanneling enters in four distinct ways. Ordinary straight crystal dechanneling is important both because it governs the rate of particle loss and because it offers a key to scaling results between different crystals and different orientations. Dechanneling inside a curved crystal ("Forster dechanneling") is more complicated since the potential well is modified[7]. Particles also dechannel entering a curved crystal ("Ellison-Kudo" dechanneling[8]). Finally, crystal defect dechanneling is potentially important. At high energies the most significant defect dechanneling is from dislocations[9].

Material properties like elasticity and the radiation length are also important. Crystal radiation damage could potentially be a significant consideration but studies by Baker et al.[10] have shown bending behavior is relatively unaffected for beam fluences up to at least $10^{18}/\text{cm}^2$.

Ordinary dechanneling scales as a function of beam energy, crystal type, and orientation.[11] Following a phenomenological treatment of dechanneling by Feldman et al.[12] (FAB) the planar dechanneling length (1/e) is:

$$\lambda = 1.62\psi^2_{cp}/\langle\theta^2_c\rangle \qquad (1)$$

ψ_{cp} is the planar critical angle and $\langle\theta^2_c\rangle$ is some approximation to the average of the square of the electronic multiple scattering in the channel. In practice, this approximation must be weighted by the initial particle distribution over the channel.

Because the channeling potential well is narrower and shallower, the dechanneling length must be modified to account for crystal curvature. Forster observed this effect using a permanently bent crystal[7]. Ellison et al.[13] have fitted Forster's results using a transverse energy diffusion model. An ansatz also gives a good fit to the Forster data including the temperature dependence. The premise of the ansatz is that the critical angle in the FAB phenomenology should be replaced by the phase space for a bent crystal channel to account for the facts that there is less available area to scatter into and that the width of the channel narrows. Because dechanneling is a diffusion process the relevant angles are squared in the formula. A good representation of the bent crystal phase space degradation is (1-F(R)) where F(R) is Ellison's dechanneling fraction. R is the crystal radius of curvature. The dechanneling length for a bent crystal is then:

$$L_b(R)=L(p)*(1-F)^2 \qquad (2)$$

The scaling behavior for small radii of curvature differs significantly between the ansatz and the Ellison model. The present Forster data does not go to small enough bending radii or, alternatively high enough energy, to distinguish between the two models. Accelerator extraction geometries do not require such small radii of curvature. For situations where bent crystal channeling is driven to the limit, such as the neutrino beam discussed later, more experimental and theoretical work would be useful.

The choice of crystals for extraction purposes is dictated by the requirement for long, perfect crystals. Germanium and silicon are by far the most perfect crystals available in large boules. Still, other materials such as tungsten have higher atomic potentials and could provide smaller bending radii. Some interesting candidates for extraction crystals include:

Silicon: Typically silicon crystals are grown with the (110) and (111) planes perpendicular to the long boule axis. For bending crystals it is important to produce boules with a (110) or (111) plane in the direction of the long axis. These silicon crystals are called dislocation-free but do have features that may be worrisome at very high energy. Samsonov[14] has studied Soviet-produced silicon and suggests the dislocation dechanneling length might be 120 mm, which would seem to place an upper limit on crystal length. Channeling has been observed up to 800 GeV in a 4.5 cm silicon crystal processed at Chalk River[15]. The authors note that the crystal transmission was anomalously low which could suggest the onset of dislocation dechanneling.

Germanium: The minimum radius for bending channeling in germanium is half as large as for silicon. As a result germanium should be able to produce a larger deflection or, alternatively, provide more transmission. Good germanium crystals are available but they have not been characterized as well as silicon.

Tungsten: Small zone-refined tungsten crystals are available. Unfortunately a metal crystal is difficult to zone refine in a large boule. Typical "good" tungsten crystals are a cm long and several mm in diameter. Their mosaic spread is in the neighborhood of 50 μrad[16]. This would limit channeling applications to below 100 GeV. The highest energy channeling reported with tungsten appears to be 0.083 GeV[17]. Reasonable channeling behavior was observed. It would be useful to extend such measurements to higher energy and also continue development and studies of the limitations of tungsten crystals.

Another parameter available in extraction system design is crystal orientation. For silicon and germanium there are three possibilities-channeling along the <110> axis or along the (110) or the (111) planes. Axial critical angles are several times larger because of the higher atomic potentials. The axial surface acceptance is larger because the beam sees rows of atoms rather than planes. Although axial bending has been observed[18], it behaves like bending channeling from several crossed planes. Several beams spill out of the crystal at widely different angles. For this reason applications up to this point have used planar channeling. For an incident beam divergence much smaller than the critical angle, axial channeling may be useful.

The (110) planar orientation has evenly-spaced planes while the (111) planes alternate between wide and narrow spacings. The dechanneling length for the wide (111) plane is longer than the (110) plane while the dechanneling length for the narrow spacing is small. Particles that enter the narrowly-spaced planes are effectively lost so the surface acceptance is lower. Nevertheless factors like dechanneling may still favor the (111) orientation.

3. Examples

Extraction from the Tevatron: The Fermilab Tevatron was designed with beam extraction in mind. Over the life of the accelerator the straight sections have filled with many other functions such as colliding beams collision regions. A possible crystal application could be to extract parasitic beam from the accelerator when it is operating in the colliding mode. This possibility has not been seriously considered.

A different strategy would be a test of channeling extraction rather than an application. One possible location is the C0 straight section near the accelerator beam abort. The abort area would be used for monitoring instrumentation. Some of the accelerator beam could be bumped out to a crystal near the abort. Another possibility is to rely on particles on the edge of accelerator phase space. This requires a good understanding of the beam phase space distribution.

Yet another possibility is to use a crystal as a surrogate for the D0 electrostatic septum which provides a 95 μrad deflection. This has the advantage of requiring no new vacuum chamber work.

A central problem is beam losses. These need to be considered carefully prior to a test.

Extraction from the SSC: Crystal extraction from the SSC has been discussed several times[6]. These studies have focused on a so-called dogleg beam which deflects the accelerator beam out to a conventional magnetic septum consisting of 65 m of Lambertson magnets. Lambertson magnets provide a field-free region close to a high magnetic field. The Lambertson magnetic field region deflects the beam back to the SSC central orbit where other dipoles return it to the central orbit. The crystal is at the edge of the beam near the start of the dogleg. Its angle is set to deflect extracted beam into the Lambertson field-free region. As a result the crystal-deflected beam leaves the accelerator.

The designers propose a 10 cm long crystal bent through a vertical angle of 95 μrad. This is a small fraction of a dechanneling length even considering Forster-type bending effects. The angle is sufficient to jump the beam 3.3 cm across a Lambertson. The beam angular divergence in a divergence-free region of the lattice is on the order of ±0.3 μrad while the critical angle is about 1 μrad. Thus the crystal easily contains most of the angular extent of the beam. There will, of course, still be loss to surface acceptance.

The designers argue the allowed beam rate loss in the SSC permits rates up to 10^9 particles/sec on the crystal. Beams of even 1% of this level would be quite useful. This is tolerable from the standpoint of crystal radiation damage. This rate is also not out of line with limits set by the possibility of magnet quenches.

This approach is conservative. Using longer crystals and larger bends might eliminate the need for the magnetic dogleg, saving 8 dipoles and 13 Lambertson magnets. A crystal bend of 500 μrad could clear the magnet at the end of the straight section. Scaling the current 800 GeV result requires a crystal only 10 cm long to produce that deflection. Even this is conservative!

Neutrino Beam Through the Earth: Several years ago De Rujula et al.[19] examined the possibility of whole-earth neutrino beam tomography. About 7% of a 1 TeV neutrino beam will be absorbed passing through the earth. Models of the earth's central core density differ by 20%. With the SSC one can envision measuring the inner core density accurately enough to resolve differences at that level. More to the point, if meter-long germanium crystals were available it is now possible to explore the problems of sending such a beam through the earth and detecting it on the other side with existing or soon-to-be-complete accelerators.

Five ingredients are necessary for a test. These are: 1) a TeV-range accelerator, 2) an extraction system to send the beam vertically downward, 3) a beam transport system to deflect the extracted beam a full 90°, 4) a 1 m diameter, 1 Km long decay pipe extending into the earth to produce neutrinos, and 5) a large detector (say 60 m by 100 m), possibly ship mounted, on the far side of the earth. Channeling could be used for two of these-vertical extraction and the troublesome 90° downward deflection.

The demands on channeling are not modest. The crystal has to be many dechanneling lengths long (between five and ten for the Tevatron using germanium). This means the crystal transmission would be extremely low. The crystals would also have to be long, several meters in the case of germanium crystals at the Tevatron. Although 90° is a large bend, the radius of curvature is larger than several recent applications. Silicon transmission is too low and a silicon septum would also be about twice as long as a germanium one. Perfect tungsten crystals would be shorter and give better transmissions but no satisfactory tungsten crystals are available.

For the Tevatron a 2.6 m germanium crystal would provide a transmission between 10^{-5} to 10^{-4}. This would be sufficient to give about 1 count/day at the detector so that a one month run would be required to get a signal. Obviously this is a very challenging program that stretches the possibilities of bent crystal channeling to the limit.

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References:

1. M. Harrison, p. 2009, and A. VanGinneken, D. Edwards, and M. Harrison, p. 2033, **Physics of Particle Accelerators**, AIP Conf. Proc. **184**, V 2 (1989).

2. G. D. Koshkarev, Inst. of Theor. and Experim. Phys. Preprint #30, 1977.

3. R. A. Carrigan, Jr., p. 339 in **Relativistic Channeling**, eds. R. A. Carrigan, Jr., J. A. Ellison (Plenum, New York, 1987). R. A. Carrigan, Jr., Fermilab FN-362 (1982). R. A. Carrigan, Jr., Fermilab 80/45 (1980).

4. V. V. Avdeichikov, et al., JINR Communication 1-84, Dubna (1984). English Translation: Fermilab FN-429 (1986).

5. M. Bavizhev-private communication. To appear in the proceedings of the 1989 UNK workshop.

6. C. H. Sun, R. A. Carrigan, Jr., T. E. Toohig, and D. Neuffer, Proc. of the 1984 Summer Study on the Design and Utilization of the SSC, p. 483 (Snowmass-1984). B. Cox, J. Lach, M. Maslov, N. Mokhov, C. T. Murphy, and R. Stefansky, 1988 Summer Study on the Design and Utilization of the SSC, (Snowmass-1988. World Scientific-Singapore, to be published). A. S. Vodopyanov et al., JINR P1-88-300 (Dubna).

7. J. S. Forster, H. Hatton, R. J. Toone, G. Este, S. I. Baker, R. A. Carrigan, Jr., W. M. Gibson, R. L. Wijayawardana, J. A. Ellison, L. Emman-Wori, B. O. Kolbesen, Nuclear Physics **B318**, 301 (1989).

8. J. A. Ellison, Nucl. Phys. **B206**, 205 (1982). H. Kudo, Nucl. Instr. Meth. **189**, 609 (1981).

9. See, for instance, L. C. Feldman, J. W. Mayer, S. T. Picraux, "Materials Analysis by Ion Channeling", Academic Press, New York (1982).

10. S. I. Baker, p. 391 in **Relativistic Channeling**, eds. R. A. Carrigan, Jr., J. A. Ellison (Plenum, New York, 1987).

11. R. A. Carrigan, Jr., Fermilab FN-454 (1987). R. A. Carrigan, Jr., Nucl. Instr. and Meth. **B33**, 42 (1988).

12. L. C. Feldman and B. R. Appleton, Phys. Rev. **B8**, 935 (1973). L. C. Feldman, B. R. Appleton, and W.L. Brown, "Solid

State Physics Research With Accelerators", Brookhaven National Laboratory Report No. BNL-50083, p. 58 (1968).

13. J. Ellison, L. Emman-Wori, R. A. Carrigan, Jr. and J. S. Forster, this conference.

14. V. M. Samsonov, p. 129 in **Relativistic Channeling**, eds. R. A. Carrigan, Jr., J. A. Ellison (Plenum, New York, 1987).

15. S. I. Baker, R. A. Carrigan, Jr., R. L. Dixon, H. C. Fenker, R. J. Stefanski, J. S. Forster, R. L. Wijayawardana, and S. Reucroft, Nucl. Instr. and Meth. **A248**, 301 (1986).

16. W. Beezhold, S. T. Picraux, Sandia National Laboratory, private communication.

17. W. Beezhold et al., Bulletin of the American Physical Society EO5, **30,** 374 (1985).

18. See, for instance, J. Bak et al., Physics Letters **93B**, 505 (1980); J. Bak et al., Nuclear Physics **B242**, 1 (1984).

19. A. De Rujula, S. L. Glashow, R. R. Wilson, and G. Charpak, Phys. Rep. **99**, 341 (1983).