Deflection of 32.8 TeV/c fully stripped Pb ions by means of a bent Si crystal

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Abstract

New results on the deflection of fully stripped 32.8 TeV/c Pb ions in a bent Si crystal at the CERN-SPS are reported. Deflection efficiencies above 10% have been measured for deflection angles in the range 4-9 mrad. The effect of particle losses due to interaction in the crystal and other systematic errors have been carefully investigated. The experimental results are in agreement with theoretical calculations.

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1 Introduction

Deflection of high energy protons in bent single crystals has been investigated in great detail and the technique is applied at various accelerator laboratories [1, 2, 3, 4, 5], using protons of up to 900 GeV/c momentum. The model description of the channeling and deflection process is found to be accurate at all energies tested so far. A natural continuation of this work appeared, therefore, to be the use of bent Si crystals in the high energy ion beams available at the CERN-SPS.

The first experiment to deflect a 32.8 TeV/c Pb ion beam by 4 mrad is reported in [6, 7], while the successful extraction, by use of a bent crystal, of 22 TeV/c Pb ions from the halo of a coasting beam in the SPS is described in [7, 8]. In the present experiment on the deflection of the 32.8 TeV/c Pb ion beam, a refined experimental apparatus was used, allowing higher accuracy measurements to be made. Various deflection angles in the range between 4 and 9 mrad could be investigated. The experimental results are compared with theoretical predictions.

2 Experiment

The experiment was located in a beam line in the North Experimental Area of the CERN SPS complex. Fully stripped lead ions (Pb^{82+}) are extracted from the SPS at a momentum 400 GeV/c per charge, 32.8 TeV/c per ion. After beam transport, splitting to serve other beam lines, and collimation to reduce the divergence of the Pb ion beam at the crystal, an intensity of some 10^5 ions per spill of 5 seconds is used. Beam deflection by means of a bent crystal takes place in the vertical plane. A schematic view of the experimental arrangement is shown in Fig. 1. The Si crystal, 1.5 mm thick in the vertical direction, 18 mm wide and 60 mm along the beam direction, is cut with the (110) planes parallel to its $18 \times 60 \text{ mm}^2$ face. The crystal is bent over 55 mm of its length with a standard 3-point bending device, as shown in Fig. 2. The bending angle can be varied by means of a micrometric screw driving the central pin of the device. The crystal is installed on a goniometer table, allowing horizontal and vertical displacements as well as rotation in both planes. The crucial movement of this goniometer for the present experiment is the vertical rotation used to align the (110) planes of the crystal with the beam. The goniometer has a step-size of $35 \mu\text{rad}$, somewhat large compared to the critical angle for channeling at 400 GeV/c momentum per charge, which is $8 \mu\text{rad}$, but comparable to the divergence of the Pb ion beam.

Figure 1: Schematic view of the experimental arrangement. Pb ions are deflected vertically by the bent Si crystal. Scintillators SC0,1 and H1-4 are tuned to detect Pb^{82+} ions. SC0 and H4 are scintillator filaments of 0.2 mm vertical height.

Figure 2: The bent crystal mounted in the 3-point bending device. The deflection angle for the Pb ion beam is varied by turning the micrometric screw, which is equipped with a digital read-out.

Two small scintillation counters were installed upstream of the crystal (cf. Fig.1). The Pb^{82+} ions were steered onto the entrance face of the crystal by aiming at scintillator SC1 (5 mm high, 2 mm thick in beam direction and 7 mm wide). Once a deflected ion beam is observed, ions from the central part of the crystal are selected by maximizing the counting rate of the deflected beam in coincidence with scintillation filament SC0 (0.2 mm high, 5 mm thick and 5 mm wide), which is installed on a remotely controlled vertical movement. Angular and position scans in this experiment are performed stepwise, with one step per SPS cycle (14.4 s). As the beam intensity may vary with time, the measurements are normalized to the number of incoming Pb ions as observed in scintillator SC0.

The deflected Pb ions were detected in a set of scintillators (socalled 'hodoscope': H1, H2, H3, each $10 \times 10 \text{ mm}^2$ in size and 5 mm thick), installed on a motorized support. The central scintillator, H2, overlaps with H1 and H3 by 2 mm in the vertical (deflection) plane. The step-size of the movement was 0.5 mm in standard operation. The accuracy for measuring the position of the beams downstream of the crystal was therefore limited by the $\text{H1} \times \text{H2}$ coincidence to be about 2 mm. This was the set-up available in the previous experiment [7]. In the present arrangement, in order to achieve a better position resolution in the vertical plane downstream of the crystal, an additional scintillation filament, H4 (identical in size to SC0), was installed next to H1.

The high voltage on all the photomultipliers of these scintillators was reduced and discriminator thresholds adjusted well above the detection level for minimum ionizing particles (typical values were -1650 V for protons, -1250 V for Pb ions). This allows Pb ions to be detected almost entirely free of background.

The beam divergence of the incident Pb ions (folded with the critical angle for channeling) was determined in two ways: (a) by measuring the intensity of the deflected Pb ion beam for varying goniometer angles, (b) by varying the incident beam angle with a combination of two vertical steering magnets (TRIMs), located 42 m and 29 m upstream of the crystal. The latter method allows step-sizes

Figure 3: Measurement of vertical beam divergence of the Pb ions. Good agreement is found between an angular scan with the crystal (dots) and a scan of the beam angle using steering magnets ($\times$).

as small as $1 \mu\text{rad}$. The agreement between the two methods is good, as demonstrated in Fig. 3 and the beam divergence is found to be $43 \mu\text{rad}$ (FWHM), i.e. slightly larger than the step-size of the vertical rotation of the goniometer. Angular scans of the beam were performed for each crystal bending angle in this experiment. The optimal alignment of the beam with the crystal, was determined in this way, i.e. as the point of highest deflected beam intensity.

The common vertical movement of the hodoscope scintillators can be performed in mini-steps of roughly $50 \mu\text{m}$, the position readout from a potentiometer allows a step-to-step accuracy in position of about $10 \mu\text{m}$. The absolute accuracy of the potentiometer, independent of the direction of movement, is estimated to be $100 \mu\text{m}$. As indicated in Fig. 1, a vertical scan will move the hodoscope upwards through the undeflected, then the deflected Pb ion beam. Examples of such scans for two different deflection angles are shown in Fig. 4. The figures in logarithmic scale show the well-known behaviour of the de-channeling region between the straight and deflected beam peaks [9, 10]: de-channeling occurs all along the crystal, but bending de-channeling is only present in the crystal region with increasing curvature, i.e. in the first half of the crystal. Moreover, as already observed with 450 GeV/c protons [11], mechanical stress due to the pin pushing on the centre of the crystal (cf. Fig. 2) causes additional de-channeling, visible as a small peak in Fig. 4d). Finally, the extremely low level of background counts below the straight and above the bent beam can be noted.

3 Experimental results

The deflection efficiency in this experiment is defined as the ratio of deflected Pb ions to Pb ions incident onto the crystal. This ratio can be deduced from scans like the ones shown in Fig. 4: the deflected ions are found in the peak to the right, while the total counting rate in the spectrum gives a measure for the incident beam (taken to be the sum of the straight, de-channeled and bent beam). While this method leads to accurate results when proton beams are used, the high interaction cross section for TeV/c Pb ions implies considerable particle losses. In fact, the integral over the full scan in Fig. 4 is found to be approximately 0.6 of the incident beam, rather than 1.0 as expected without interaction losses. This source of systematic uncertainty was investigated in more detail. Vertical hodoscope scans were performed and compared for the straight beam alone (without crystal) as well as for a non-aligned crystal in the beam. (No-crystal scans provide a measure for the combined inefficiency of scintillation counters

Figure 4: Vertical hodoscope scans with mini-steps for 4.3 mrad (a+b) and 8.5 mrad (c+d) deflection angle. The logarithmic scales in b) and d) exhibit the de-channeling tail between the straight and the deflected beam peaks.

Figure 5: Vertical hodoscope scans through the straight beam peak with 2 mm (a) and 0.2 mm (b) position resolution. Scans without a crystal (+) and with a non-aligned crystal (open squares) are shown. The difference between the two measurements allows the Pb ion interaction losses in the crystal to be determined.

and coincidence electronics.) Results are shown in Figs. 5a) for the “rough” scans using $SC0 \times H1 \times H2$ and in Fig. 5b) for mini-step scans recording $SC0 \times H4$. Fitting and integrating these data, one finds a loss of detected Pb ions due to interactions of $37 \pm 1\%$. The width of the beam profiles measured in mini-steps (Fig. 5b)) is found to be 0.12 mm (1σ) for the no-crystal case (i.e. dominated by the width of the scintillators) and 0.24 mm for the non-aligned crystal (due to multiple scattering of Pb ions in Si). Note that a $SC0 \times H4$ scan, even when performed with very small steps, will never provide full overlap between the two 0.2 mm scintillator filaments. Moreover, some inefficiency of the thin scintillators must be expected - thus the value of around 0.5 attained in Fig. 5b).

Integrating the deflected beam peak and dividing by the total number of counts measured in vertical scans (cf. Fig. 4) gives the deflection efficiency after applying the correction factor for nuclear interactions of 0.63 found experimentally. Results obtained for deflection angles between 4 and 9 mrad are summarized in Table 1 and shown in Fig. 6. The triangles in the figure represent data points obtained from mini-step scans, while the open squares are obtained with the standard scans of 0.5 mm step-size. The error bars shown are systematic errors, the statistical error is negligibly small. The uncertainty in the deflection angle (equal to or smaller than the width of the symbols in Fig. 6) stems from the size of the scintillation counters used and the step-size of the vertical scans, while the uncertainty in the deflection efficiency is due to the potentially non-perfect overlap between the the scintillators used ($SC0$ and $H4$ for mini-step scans, $SC0$ and $H1 \times H2$ for the standard scans) and the resulting loss in coincidence counting rate.

Table 1: Measured deflection efficiencies for the 32.8 TeV/c Pb ions, compared to theoretical predictions. Statistical errors in the experiment are negligible; systematic errors are given. For more details, see text.

deflection angle	deflection efficiency experiment	deflection efficiency simulation
4.3 mrad	$13.0 \pm 1.5 \%$	11.5 %
5.8 mrad	$11.5 \pm 1.5 \%$	10.6 %
6.8 mrad	$9.3 \pm 1.5 \%$	9.9 %
8.5 mrad	$8.6 \pm 1.5 \%$	8.6 %
8.9 mrad	$9.0 \pm 1.5 \%$	8.0 %

The data show the expected tendency of lower efficiency for larger deflection angles. This can be attributed to the increased bending de-channeling losses, as observed previously with protons [12]. The values of the deflection efficiency appear to be low compared to the record of above 50% observed with protons [12]. This, however, is mostly due to the divergence of the incident beam, which is about ten times larger in the present experiment - a “micro-beam” could not be produced with the Pb ions due to lack of intensity, and no drift chambers were available for off-line cuts on the incident angles and positions of the ions hitting the crystal.

4 Model calculations

The deflection efficiency for Pb ions in a bent Si crystal was predicted by a Monte Carlo simulation, analogous to earlier work for proton deflection [13, 14, 15, 16]. The particle trajectories were calculated in the averaged potential of the bent atomic planes, and the change in transverse velocity of the particle due to multiple scattering by the crystal electrons and nuclei was performed in steps along the trajectory, which were much smaller than the spatial period of particle oscillations in the channel. Moreover, the probability for inelastic nuclear interactions of the Pb ions was taken into account at every step. The model uses realistic distributions of electron and nuclear densities in the crystal channel. The calculation

Figure 6: Experimental deflection efficiency vs. deflection angle, compared to model predictions. Triangles refer to results obtained with mini-step scans, squares to results from scans with 0.5 mm step-size. For further details, see text.

of the planar potential and electron density was performed in the Molière approximation with thermal vibrations of the crystal atoms included [17].

From general channeling theory, it is known that the critical angle for channeling, the surface transmission (i.e. the 'acceptance') and the de-channeling due to multiple scattering are equivalent for different particles of the same momentum per charge [10]. For 32.8 TeV/c fully stripped Pb ions, the values found for 400 GeV/c protons can thus be applied. For (110) planes in Si, the critical angle is found to be $\psi = 8.37 \mu\text{rad}$. The critical radius for deflection, often referred to as 'Tsyganov'-radius, is $R_c = 67 \text{ cm}$ [18], corresponding to a deflection angle of 41 mrad in the present experiment.

The experimental angular scans (cf. Fig. 3) were used to give the angular distribution of the incident beam in the simulations. This is a correct procedure because the angular scan is much wider than the critical angle ψ .

The curvature of the crystal produced by the 3-point bending device is non-uniform with a maximum near the central point $\kappa_m = 2 \kappa_o$, where $\kappa_o = 1/R_o = \alpha/L$ is the average curvature which is created when the part of the crystal with length $L = 55 \text{ mm}$ is uniformly bent by the angle α . The real crystal shape was approximated in the simulations: It was assumed that the crystal curvature increases linearly up to the central point.

A major difference between protons and Pb ions stems from the probability for inelastic nuclear interactions. The corresponding cross-section increases with the atomic weight of the nuclei A , $\sigma_{in} \sim A^{0.71}$ [19]. The nuclear interaction length, $L_{in} = 1/n\sigma_{in}$, where n is the nuclear density of the material, equals 45.5 cm for relativistic protons and approximately 1 cm for relativistic $^{208}\text{Pb}^{82+}$ ions in amorphous Si or, equivalently, a non-aligned Si crystal.

For Pb ions incident parallel to e.g. the (110) plane of a crystal, the target nuclear density changes in the transverse direction x . The density distribution $P_n(x)$ depends upon the thermal vibration amplitude u_1 of the crystal atoms. The nuclear interaction length $L_n(x)$ changes correspondingly. Therefore, for

an aligned crystal,

$$n(x) = nP_n(x) \ , \quad L_n(x) = L_{in}/P_n(x) \ , \quad (1)$$

$$P_n(x) = \frac{d_p}{(2\pi u_1)^{1/2}} \exp(-x^2/2u_1^2) \ , \quad (2)$$

where d_p is the channel width (for (110) Si, $d_p = 1.92$ Å). Fig. 7 shows the nuclear interaction length for protons and Pb ions as a function of the distance from the (110) plane in a Si crystal at room temperature, where $u_1 = 0.075$ Å. It is about ten times smaller than L_{in} in the planes of atoms, becomes equal to L_{in} at $\bar{x} = u_1(2 \ln(d_p/\sqrt{2\pi u_1^2}))^{1/2} = 1.617$ Å, (roughly twice the amplitude of thermal vibrations) and then it increases rapidly towards mid-distance between the atomic planes.

The computer simulation registers the particles at many locations along their trajectory in the crystal. Fig. 8 shows the calculated dependence of the number of channeled particles which have transverse motion in the planar channels, on the position along the crystal. Note that the initial number of ions is 20000 in these simulations - the calculated deflection efficiency in % is therefore the number of channeled ions at the exit of the crystal divided by 200. Results are given in Table 1 and shown as a solid line in Fig. 6. Good agreement between experiment and simulations is observed.

The number of nuclear interaction events, shown in Fig. 9, is due mainly to non-channeled ions. While in amorphous Si this would lead to an exponential behaviour, the number of interactions is modified here due to the ions which are initially channeled, but dechannel along the bent crystal.

Finally, it should be mentioned that this computer simulation was also performed for a straight crystal. It was found that the dechanneling length for relativistic Pb ions equals 10.4 cm in (110) planes of Si. This result cannot be verified with the experimental techniques described above. Instead, a crystal equipped with several surface barrier dE/dx detectors distributed over its length (as used e.g. in [11]) could provide a measurement of the “non-bent” dechanneling length. Contrary to the proton case, this

Figure 7: Inelastic nuclear interaction length for relativistic protons and Pb ions, as a function of their transverse distance from (110) planes in a Si crystal. The values for amorphous Si are indicated as ‘random’.

might be difficult to observe with Pb ions due to their very high energy loss (about 2 MeV per μm in amorphous silicon).

Figure 8: Result of computer simulations: For a total of 20000 ions incident, the number of channeled ions at various locations along the bent crystal is shown for two examples, deflection angle: 4.3 and 8.9 mrad.

Figure 9: Number of interacting ions per bin of 2.5 mm along the crystal, for the two deflection angles 4.3 and 8.9 mrad. Note the slightly higher numbers for the case of 8.9 mrad (open dots), which can be attributed to the larger fraction of dechanneled ions in the bent part of the crystal.

5 Summary and Outlook

The deflection by a bent silicon crystal of 32.8 TeV/c fully stripped Pb ions has been investigated with refined experimental techniques. Deflection efficiencies higher than 10% have been observed in the range of bending angle 4-9 mrad, in good agreement with theoretical predictions. This result further corroborates the potential of bent crystal applications in particle and ion beams and as extraction devices at accelerators, e.g. the Nuclotron at Dubna [20], RHIC at Brookhaven - where a collimation scheme with a bent crystal is being installed [21, 22] - or at the LHC at CERN.

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