FIRST OBSERVATION OF THE DEFLECTION OF A 33 TeV Pb ION BEAM IN A BENT SILICON CRYSTAL

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Abstract

For the first time, the deflection of an ultra-relativistic, fully stripped Pb^{82+} ion beam in a bent silicon crystal has been observed. The ions were provided by the CERN-SPS in the H4 beam at a momentum of 400 GeV/c per unit of charge. A 60 mm long silicon crystal, bent over 50 mm to give a 4 mrad deflection angle, was used in this experiment. The measured Pb ion deflection efficiency is comparable to the one obtained with protons at an equivalent ratio of momentum per charge, and is found to be about 15% for a beam with a divergence of 35 microradians (FWHM). The interaction rate observed in a background counter is found to drop when the crystal is well aligned with the beam. This corroborates further the channeling model, which predicts that channeled ions are steered away from regions of high electron densities as well as the nuclei in the crystal.

1 INTRODUCTION

During the past ten years, the deflection of high energy proton beams by planar channeling in bent silicon crystals has been intensively studied and this technique is now being applied routinely at accelerator laboratories around the world [1], [2], [3], [4]. Planar channeling, the steering of particles by the collective fields of crystalline planes, takes place when particles enter the crystal within a small angle (the so-called critical angle) to these planes. For small bending angles, channeling persists throughout the full crystal length.

Apart from the attraction of a bent crystal as a cheap and easy way to extract and split particle beams, it has been astonishing to see how well the channeling models, originally developed for MeV particles, still apply at the highest energies available at proton accelerators today, i.e. up to 900 GeV. Recently, the validity of the models for planar deflection were also tested in a different material, i.e. a germanium crystal, and very good agreement was found [5]. Ions, on the other hand, have hardly been used in connection with bent crystals at accelerators, the only exception being an early test with 53 GeV/c C^{6+} nuclei at Dubna [6], where a deflection efficiency could not be measured. Predictions for bent crystal assisted beam extraction from the heavy ion accelerators in Dubna and Brookhaven are available since a few years [7]. With the availability of the ultrarelativistic Pb ion beam at CERN, it was thus of particular interest to try and deflect such a very high energy beam with a bent crystal.

The fully stripped 33 TeV Pb ions challenge the experimenter further due to the high background (δ-electrons, pions, etc.) observed wherever such ions pass material or, worse, are stopped in a beam-line aperture limitation. Special precaution has therefore to be taken to identify Pb ions in the detectors and to distinguish them from lighter particles with lower charge leading to background events. The high charge state, however, provides one with a very strong signal from Pb ions passing the detectors based on energy loss or scintillation. While many experiments turn to Cerenkov counters for clean Pb ion identification, in the present case standard scintillation counters were used with photomultipliers run at a strongly reduced gain compared to that used for singly charged relativistic particles.

On the other hand, the large number of interaction products from Pb ions passing through material allows to test one of the hypothesis' of channeling theory: Positively charged channeled particles are steered through the crystal at large impact parameters, i.e. away from the lattice nuclei, and channeled ions should thus experience a reduced interaction rate compared to non-channeled ions.

2 EXPERIMENT

The experiment was carried out in the H4 beam line in the North Area of the CERN-SPS. The beam was calculated to be parallel in the vertical plane, in which the deflection by the bent crystal should take place. The experiment was performed in three phases: (a) In order to verify the experimental arrangement and test the detectors, a proton deflection experiment with a 450 GeV/c beam from the SPS was performed prior to the Pb ion run. This test gave confidence that the bent crystal deflected protons as efficiently as expected from the experience acquired over the past years. (b) The $^{208}Pb^{82+}$ ions with a momentum of 400 GeV/c per charge, thus 32.8 TeV/c, were used in a first option with more generous collimator settings, resulting in a wider vertical angular distribution with a FWHM of 50 μrad, very similar to the beam divergence in the proton run. With this beam, the first Pb ion deflection experiment was performed. (c) Finally, the same Pb ion beam, but with more restrictive collimator settings, was found to have a vertical angular distribution of 35 μrad (FWHM), leading to a higher de-

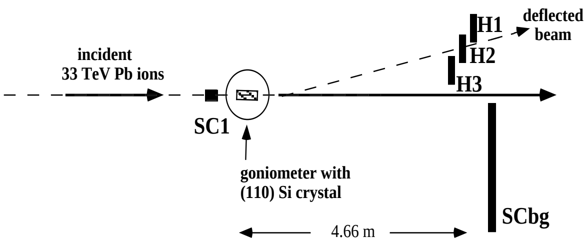

Figure 1: Schematic view of the experimental arrangement. Pb ions are deflected vertically by the bent silicon crystal. Scintillators Sc1 and H1, H2, H3 are tuned to detect Pb^{82+} ions, while SCbg is tuned for background particles.

flection efficiency (see Table 1 below).

The experimental arrangement is schematically shown in Figure 1. The location in the H4 beam, equipped with a goniometer on an x-y translational table, was originally prepared for tests of proton beam splitting in a bent crystal in view of the NA48 CP violation experiment [1]. The crucial movement of the goniometer for the present experiment, i.e. the vertical rotation used to align the (110) planes of the crystal with the beam, has a step-size of 35 μrad, somewhat large compared to the critical angle for channeling at 400 GeV/c/Z momentum, which is $\pm$ 8 μrad, but similar to the Pb ion beam divergence.

The Pb^{82+} ions were steered onto the entrance face of the 1.5 mm thick crystal by aiming at a small scintillator (SC1, 2 mm high, 5 mm thick and 7 mm wide) installed upstream of it. The crystal, 60 mm long in beam direction and 18 mm wide, was bent over 50 mm of its length in a new version of the now 'classical' three-point bending device, which is described in [5]. The resulting bend angle for this experiment was 4 mrad. The deflected Pb ions

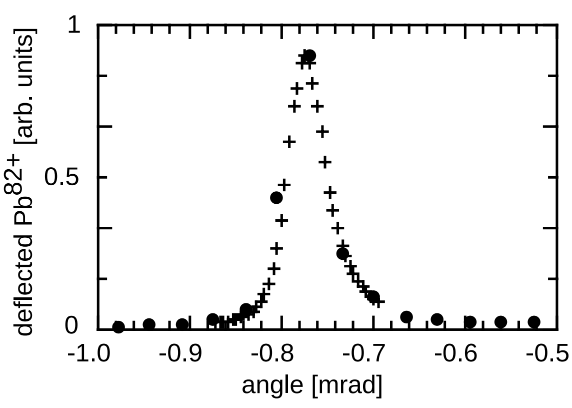

Figure 2: Measurement of the Pb ion vertical beam divergence. Good agreement is found between an angular scan with the crystal (dots) and a scan of the beam angle using steering magnets (+).

were detected in a set of three scintillators ('hodoscope': H1, H2, H3), each 10*10 mm^2 in size and 5 mm thick in beam direction, installed on a motorised support. The central scintillator, H2, overlaps with H1 and H3 by about 2 mm in the vertical (deflection) plane. The high voltage on the photomultipliers of these scintillation counters was reduced and discriminator thresholds adjusted well above the detection level for minimum ionising particles (typical H.T values were -1650 V for protons, -1250 V for Pb ions). An additional scintillation counter (SCbg), 100*100 mm^2 in size and 10 mm thick, was installed outside the beam in order to detect the interactions produced by lead ions passing through the crystal. Thus, its high-voltage was adjusted to a level just below the one used for minimum ionising particles. The beam divergence of the incident Pb ions 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 elements (TRIMs), located 42 and 29 meters upstream of the crystal. These magnets allowed to change the incident angle without changing the beam position at the crystal. Typical results for both types of angular scans are shown overlayed in figure 2 for the first experiments with a larger beam divergence. The agreement between the two methods is excellent, and the divergence in this case is found to be 50 μrad (FWHM).

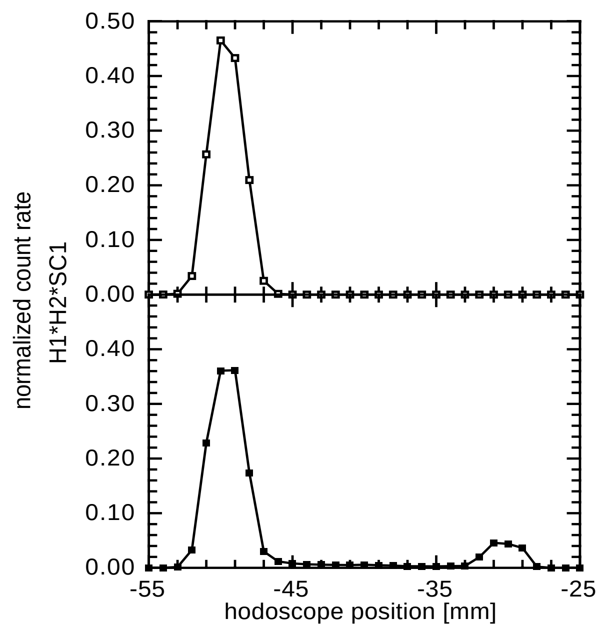

Figure 3: Vertical scan of the hodoscope (stepsize 1 mm) for the more divergent ('wide') Pb ion beam. For a non-aligned crystal (top), the straight beam peak is visible. Its intensity is reduced for the well-aligned crystal (bottom), and an additional peak of upwards deflected Pb ions is visible. (Note: The integrated number of counts is very similar in the two plots.)

3 RESULTS

The undeflected and deflected Pb ions downstream of the crystal can be detected in a given hodoscope scintillator by scanning the hodoscope vertically through the beams. The best position resolution (about 2 mm) in such a scan is obtained when the coincidence between two overlapping scintillation counters, e.g. H1*H2, is used. The result of such a scan, for the case of the larger Pb beam divergence, is shown in Figure 3. The top of this figure shows the scan for a non-aligned crystal, while the bottom shows the result for a well-aligned crystal. In Figure 4, the same result

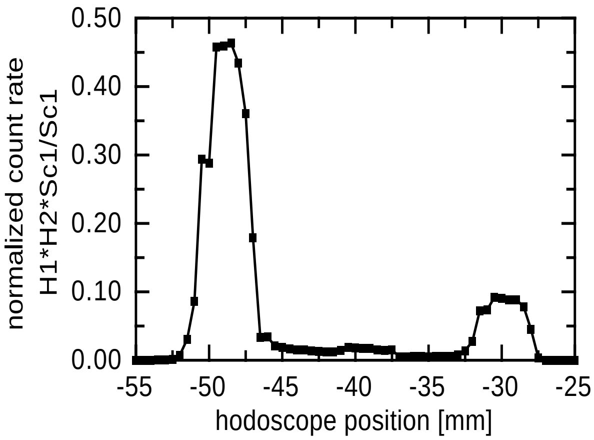

Figure 4: Vertical scan of the hodoscope (stepsize 0.5 mm) for the less divergent ('narrow') Pb ion beam. The coincidence rate in the overlapping counters H1*H2, for ions which passed through SC1, is measured and normalised to the incoming beam rate. The undeflected beam is shown at -49 mm, 19 mm lower than the Pb ions deflected by the crystal. Some ions, visible between the two peaks, were intially channeled and later lost in the bent part of the crystal.

is shown with smaller step-size for the narrow angular distribution of the incident Pb ion beam. Here, the straight and deflected Pb ions are clearly visible, and a region of partially deflected (i.e. initially channeled and then lost) ions can also be seen. Not visible in Figure 3 and 4 is the excellent background rejection of the counters: below the straight as well as above the bent beam, zero counts have been recorded.

Analysing the integrated count rates in such a scan, the deflection efficiency can be deduced as the ratio between the deflected and the incident Pb ions. Results are summarized in Table 1. For the undeflected beam peak, a correction concerning the interactions in the crystal has to be applied to the integral found in the hodoscope scan. The size of this correction in the present case can be estimated from the observation that only 65% of the ions counted in SC1 are detected in SC1*H2, downstream of the crystal, for the non-aligned case (cf. upper part of Fig.3). The remaining systematic errors in the efficiency analysis stem from two sources: (1) The efficiency may be underestimated due to the fact that SC1 is thicker than the crystal (2 vs. 1.5 mm), and the beam is wider than both, FWHM about 3.5 mm. The results presented here have been corrected for this effect. The uncertainty introduced in the efficiencies is estimated to be 1%. (2) The efficiency may be wrongly estimated depending on the cut that is chosen around the bent beam peak in Fig. 3 and 4. (A report comparing the measured deflection efficiencies for Pb ions with those calculated by A. Taratin's simulations is in preparation.)

The observed interaction rate in the 'background' counter SCbg (cf. Fig. 1) is found to drop by about 15% for a well-aligned crystal (at the peak in Fig. 2), i.e. where the largest fraction of Pb ions is channeled and deflected by the crystal. This observation is in agreement with the expectation based on channeling theory: well channeled ions are steered through the crystal far away from the nuclei, and the probability for interactions is thus reduced. The results obtained with the 'background' counter during angular scans will be reported in more detail elsewhere.

Pb beam	divergence	deflection efficiency
'wide' beam	50 μrad	8±2 %
'narrow' beam	35 μrad	14±2 %

Table 1: Measured deflection efficiencies for the 33 TeV Pb ions. Statistical errors are negligible; systematic errors are given. For more details, see text.

4 CONCLUSION

The present experiment has, for the first time, shown the feasibility of deflecting a very high energy, fully stripped Pb ion beam by means of a bent crystal. The experimental results are corroborating the channeling model widely used for protons at energies from MeV to TeV. In addition, the deflection efficiency for these ions is comparable to the one for protons, assuming an equivalent beam emittance and crystal geometry. This is all the more positive as one might have feared a strong loss of ions due to interactions with the atoms in the crystal lattice. The present results can be seen as a first, encouraging step towards extracted ion beams at the Nuclotron (Dubna) and at RHIC (Brookhaven), as proposed by [7].

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