Deflection and Extraction of Pb Ions up to 33 TeV/c by a Bent Silicon Crystal

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The first results from an experiment to deflect a beam of fully stripped, ultrarelativistic Pb^{82+} ions of 400 GeV/c per unit of charge, equivalent to 33 TeV/c, by means of a bent crystal are reported. Deflection efficiencies are as high as 14%, in agreement with theoretical estimates. In a second experiment a bent crystal was used to extract 270 GeV/c-per-charge Pb^{82+} (22 TeV/c) ions from a coasting beam in the CERN-SPS, and a high extraction efficiency of up to 10% was found. These represent the first measurements to demonstrate applications of bent crystals in high energy heavy ion beams. [S0031-9007(97)04627-9]

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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 [1–4]. 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 can persist throughout the full length of the bent crystal. Recent reviews of the physics of beam deflection with bent crystals and its applications at accelerators can be found in Refs. [3,5].

Apart from the attractiveness of using a bent silicon crystal as a cheap and easy way to extract and split positively charged 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 [2]. Recently, the validity of the models for planar deflection were also tested in a different material, i.e., a germanium crystal, and, again, very good agreement was found [6]. 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 [7], where the deflection efficiency could not be measured. Model calculations for bent crystal assisted beam extraction from the heavy ion accelerators in Dubna and Brookhaven have been made [8].

With the availability of the ultrarelativistic Pb ion beam at the CERN-SPS [9], it was of particular interest to test the principles of channeling and deflection with this very high energy beam. This was done in two stages. In an external beam line, the available 33 TeV/c Pb ions (corresponding to 400 GeV/c per unit charge, the standard momentum for an extracted Pb ion beam at the SPS) were deflected in a bent crystal under well-controlled beam conditions. In the second experiment, 22 TeV/c Pb ions (corresponding to 270 GeV/c per unit charge, the maximum momentum for a stored beam in the SPS) were slowly extracted by means of a bent crystal from the halo of a stored beam in the accelerator. The measurements and results of both experiments are described in this paper.

The main difference between Pb^{82+} ions and protons is the high mass and charge state. Both have an impact on the interaction of the ions with the crystal and the surrounding material (bending device, mechanical support). The three important parameters for channeling and deflection, i.e., the critical angle ψ_p, the dechanneling length, and the multiple scattering, are expected to depend upon Z and p only through the ratio of momentum and charge, p/Z. Therefore, the deflection of highly charged ions behaves like the deflection of protons of the equivalent momentum per charge. For example, the critical angle for planar channeling in the (110) plane in silicon is about 9.5 μrad for both, 270 GeV/c

protons and 22 TeV/c fully stripped Pb ions. The multiple scattering in amorphous material (and in a nonaligned crystal) is of particular importance in the extraction experiments [4,10]: Particles or ions in a circular accelerator, which are not channeled and undergo small angle scattering in the first pass through the crystal, may stay within the acceptance of the accelerator and hit the crystal again at a later turn. Once they happen to be within the critical angle for channeling, such particles may be extracted at a later turn. This effect has been found to be of importance for proton extraction [10] and is referred to as multipass extraction.

Protons with a momentum up to 270 GeV/c have been extracted from the SPS [11], while proton deflection in an external beam is routinely performed at 450 GeV/c [1]. The corresponding experiments with fully stripped Pb ions thus seem feasible.

However, due to the dependence of the nuclear cross section on the atomic mass, the losses due to inelastic collisions are strongly increased for ions incident on amorphous material. Worse, the electromagnetic (Weizsäcker-Williams) break-up cross section is very large for such highly charged, fast ions. Nevertheless, channeling helps to suppress this effect: Channeled positive ions are steered away from the nuclei and regions of high electron densities in the crystal, and the interaction rate for channeled ions is expected to be strongly decreased [5] with respect to nonchanneled ions. This is apparent in computer simulations [12] (cf. Fig. 1) of the 33 TeV/c Pb ion deflection experiment described below. The number of nuclear interactions ΔN_{nuc} along the crystal is due mainly to nonchanneled ions. While in amorphous silicon, this would be determined by the interaction length of about 1 cm and result in an exponential behavior; the number of interactions is slightly modified in the present case due to ions which are dechanneling along the bent crystal. The number of channeled ions N_{ch} is given basically by the incident beam divergence and the dechanneling processes, just as in proton deflection [5].

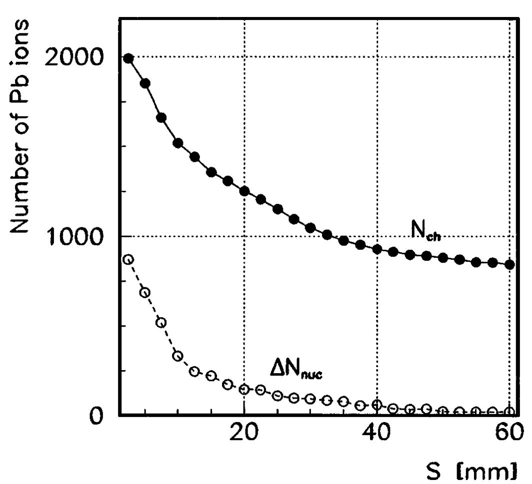

FIG. 1. Computer prediction of the Pb beam deflection experiment: 5000 Pb ions passing through a 60 mm long silicon crystal along the (110) planes, bent to 4 mrad. N_{ch} denotes the number of channeled ions and ΔN_{nuc} denotes the number of nuclear interactions along the crystal.

Once an ion is channeled, nuclear interactions play only a minor role in its fate. The predictions shown in Fig. 1 are encouraging: Over 800 ions out of 5000 are expected to be channeled through the full length of the bent crystal, corresponding to a deflection efficiency of 16.8% (cf. Table I). The model contains a (relative) error of about 15%, stemming from uncertainties in the channeling potential and electron density distributions in the crystal.

The Pb ion deflection experiments were carried out in a beam line in the north area of the CERN SPS. The beam was designed to be as parallel as possible in the vertical plane, in which the deflection by the bent crystal takes place. Two experiments with the same beam optics but different collimator settings were performed, resulting in a slightly different ion beam divergence (cf. Table I). The experimental arrangement is schematically shown in Fig. 2.

The Pb^{82+} ions were steered onto the entrance face of the 1.5 mm thick crystal by aiming at a small scintillator (SC1) installed just 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 [6]. The resulting deflection angle for this experiment was 4 mrad. 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, but similar to the Pb ion beam divergence. This goniometer was used to prealign the crystal with respect to the ion beam.

The deflected Pb ions were detected in a set of three scintillators (forming a "hodoscope": H1, H2, H3), installed on a motorized support. The divergence of the incident Pb ions was determined by measuring the intensity of the deflected Pb ion beam for varying incident beam angles, using a combination of two vertical steering elements. This method allows step sizes as small as 1 μrad, thus giving the accurate crystal alignment needed for the deflection experiment.

The undeflected and deflected Pb ions downstream of the crystal can be detected in a hodoscope scintillator by scanning the hodoscope vertically through the beams (cf. Fig. 2). The best position resolution (about 2 mm) in such a scan is obtained when the coincidence between two

TABLE I. Measured deflection efficiencies for the 33 TeV/c Pb ions, compared to theoretical predictions. Statistical errors are negligible; systematic errors are given.

Pb beam	Divergence	defl. efficiency experiment	defl. efficiency theory
"wide" beam	50 μrad	$(8 \pm 2)\%$	$(10.5 \pm 1.6)\%$
"narrow" beam	35 μrad	$(14 \pm 2)\%$	$(16.8 \pm 2.5)\%$

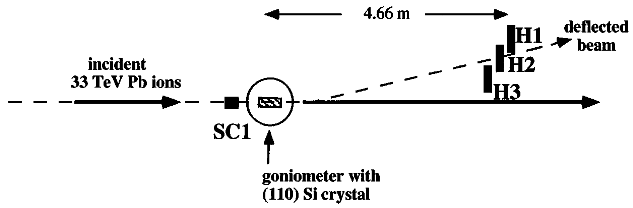

FIG. 2. Schematic side view of the deflection experiment. Pb ions are deflected 4 mrad vertically by the bent silicon crystal. Scintillators SC1 and H1, H2, H3 are tuned with high threshold to detect only Pb^{82+} ions.

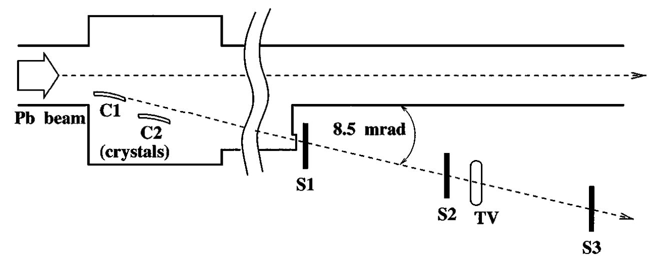

FIG. 4. Schematic top view of the extraction experiment. Two crystals can be used alternatively to extract Pb ions horizontally to the scintillators S1–S3. The luminescent screen equipped with a CCD camera is indicated by "TV."

overlapping scintillation counters, e.g., H1*H2, is used. The result of such a scan, for the case of the smaller Pb beam divergence, is shown in Fig. 3. 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. Analyzing 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. Details of this analysis are given in [13]. The results are summarized and compared to the theoretical predictions in Table I. Given the uncertainties, both in this first experiment and in the theoretical model, the agreement is very good.

The experimental procedure for the Pb ion extraction experiment at the SPS is similar to the one used for the extraction of protons [4,11]. Here, a stored beam of Pb^{82+} ions is used and hence the momentum is 22 TeV/c. The beam is artificially blown up by small stochastic kicks in the horizontal plane in which the extraction takes place using a pair of deflector plates. Ions diffusing out to the crystal located in the halo (about 10 mm from the beam center) can channel and thus be deflected and extracted, provided the impact angle lies within the critical angle. In the extraction experiment, a 40 mm long, 1.5 mm thick silicon crystal cut in a particular "U shape," is bent uniformly to provide a deflection angle of 8.5 mrad for channeled particles along the (110) planes [4]. The crystal is mounted on a goniometer, allowing its alignment with the incident ions in the horizontal plane. The coincidence of three scintillation counters is used to count extracted particles, and a luminescent screen allows the real-time observation of the extracted beam (see Fig. 4). The gain of these detectors was reduced with respect to the earlier proton experiments, thus allowing the suppression of a part of the interaction products stemming from the crystal and surrounding material. Angular scans were taken at different times during the experiment to study the reproducibility. An example is shown in Fig. 5. After the background in such scans of 20%–25% is subtracted, the full width at half-maximum (FWHM) of the scan in Fig. 5 is about 50 μrad, significantly narrower than the ones measured for protons between 14 and 270 GeV/c [11]. One may speculate whether these narrower angular scans are due to a suppressed contribution of multipass extraction to the total extracted rate. Profiles of the extracted beam were measured with the luminescent screen and a CCD camera, and could be digitized and stored. Here, the background of light particles (stemming from nuclear interactions) is completely suppressed in the profiles due to the strongly reduced gain. The results can be seen in Fig. 6. The profiles are similar to the ones obtained with the scintillator hodoscope for protons [4,11]. The vertical beam profile is always found to be wider due to the effects of multiple Coulomb scattering

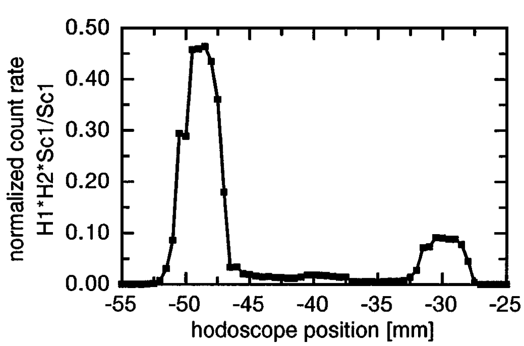

FIG. 3. Vertical scan of the hodoscope (step size 0.5 mm) for the less divergent ("narrow") Pb ion beam. The undeflected beam is shown at −49 mm, 19 mm lower than the Pb ions deflected by the crystal. Some ions, visible between the two peaks, were initially channeled and later lost in the bent part of the crystal.

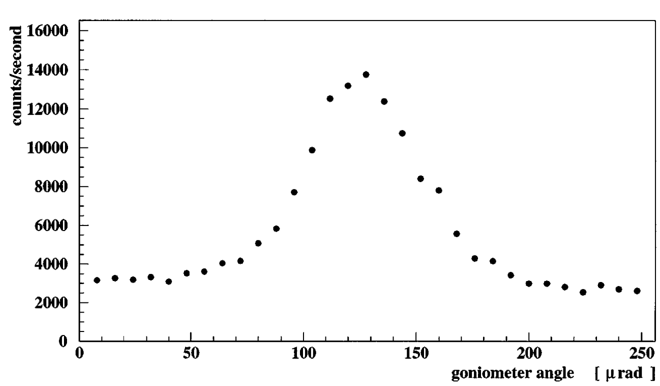

FIG. 5. Angular scan for extracted Pb ions from a stored SPS beam, 270 GeV/c per charge (22 TeV/c).

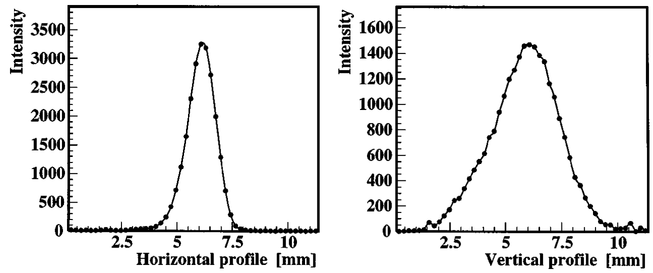

FIG. 6. Horizontal and vertical profiles of the extracted Pb ion beam for optimum alignment of the crystal (i.e., at the peak in Fig. 5).

(MCS) and multiple passes through the crystal before extraction. The width of the horizontal profile is given by the critical angle for channeling, while MCS in the material downstream of the crystal contributes equally to the width of both profiles. We define the efficiency of the extraction process as the ratio of the number of extracted particles I_{extr} to the number of particles lost from the circulating beam I_{lost}, i.e., we make the assumption that all particles are lost due to the presence of the crystal,

$$\epsilon_{\mathrm{extr}} = \frac{I_{\mathrm{extr}}}{I_{\mathrm{lost}}} . \qquad (1)$$

The number of extracted ions is determined from a threefold coincidence of scintillation counters $S1^{*}S2^{*}S3$ and the background estimated from the measured angular scans (cf. Fig. 5) is subtracted. The number of particles lost from the beam is determined from the beam intensity measured with a beam-current transformer (BCT) at 19.2 s intervals. This is equivalent to measuring the beam lifetime. For the calculation of the efficiency we use rather conservative values and estimate a relative error on the efficiencies of approximately 35%–40%. This error is larger than reported for protons [4] and is governed by uncertainties on the beam lifetime as well as on the background subtraction. The results of our efficiency estimates are given in Table II for four different excitation levels, i.e., different beam lifetimes. For the first four measurements in Table II the standard U-shaped crystal [4] was positioned at a distance of about 10 mm from the closed orbit. For the last measurement an alternative crystal was used at a larger distance of approximately 20 mm from the orbit. Significant differences were not observed between the two types of crystals.

Compared with the measured efficiency from proton extraction at 270 GeV/c, which was about 18% [11], the efficiencies for lead are about a factor of 2 smaller and the spread of the measured efficiencies is slightly larger. A possible dependence of the efficiency on the beam lifetime (i.e., the diffusion speed) cannot be proven nor excluded.

In conclusion, the deflection of fully stripped, ultra-relativistic Pb ions at 33 TeV/c as well as the slow extraction of 22 TeV/c Pb ions by means of a bent silicon crystal have been demonstrated for the first time. In the deflection experiment, which is a single-pass measurement performed under well-controlled beam conditions, the efficiencies compare well with theoretical predictions. This corroborates further the classical channeling models, already well proven for protons at all available energies. The situation in the extraction experiment is more complex: the ion beam incident on the crystal cannot be observed without perturbing it, and, in a circular accelerator, ions can be scattered first and channeled/extracted at later turns. Such multipass effects, although expected to be suppressed for ions due to the high interaction probability, make predictions more difficult. The extraction efficiency of up to 10% observed in this first attempt is therefore an encouraging demonstration of the feasibility of the crystal technique also for ion extraction. It renders possible the parasitic extraction of ion beams at the high energy heavy ion accelerators.

TABLE II. Extraction efficiencies for Pb ions at 22 TeV/c.

Circulating beam intensity (10^7 ions)	Beam lifetime (h)	Extraction efficiency (%)
13.0	2.2	4.0 ± 1.5
10.0	0.3	10.0 ± 3.5
6.7	1.2	9.0 ± 3.0
5.0	0.04	11.0 ± 4.0
5.0	0.23	5.0 ± 2.0

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