WHAT DID WE LEARN FROM THE EXTRACTION EXPERIMENTS WITH BENT CRYSTALS AT THE CERN SPS ?

K. Elsener, G. Fidecaro, M. Gyr, W. Herr, J. Klem, U. Mikkelsen, and E. Weisse CERN, SL Division

Abstract

The feasibility and properties of particle extraction from an accelerator by means of a bent crystal were studied extensively at the CERN SPS. The main results of the experiments are presented. This includes the evidence for multi-pass extraction, energy dependence of the efficiency and the extraction of heavy ions. These results are compared with theoretical expectations and computer simulations.

1 INTRODUCTION

The principle of proton extraction using channeling in bent crystals was demonstrated in Dubna and Protvino [1, 2]. Following this successful experience, experiments were performed at the CERN SPS between 1992 and 1996. The purpose of this experimental programme was to demonstrate the feasibility of such an extraction scheme at the LHC where the extraction would be parasitic to the normal collider operation. A good understanding of the extraction process and of the parameters which determine the efficiency was therefore the main aim.

2 THE PRINCIPLES

Particles entering the crystal with the right conditions are trapped between the crystalline planes, even when the crystal is slightly bent, and can therefore be deflected. When such a bent crystal is placed into the halo of a circulating beam, the large amplitude particles entering the crystals can be deflected away from the beam and are eventually extracted. For a successful extraction, several conditions must be fulfilled: First, the crystalline planes have to be aligned with the beam because the relative angle between the planes and the particle direction must be smaller than the so-called critical angle $_c$ [7]. Secondly, the particles must enter deep enough into the crystalline structure to overcome possible surface imperfections, i.e. the impact parameter b must be large enough. This has always been a strong concern in the design of an extraction scheme which operates parasitically to normal operation, i.e. without a deterioration of the beam life time.

2.1 First- and multi-pass extraction

Usually, the obtainable impact parameters are smaller than the inefficient layer, which is typically in the order of micrometers, in particular if the lifetime of the beam is required to be sufficiently large. Particles in this surface layer cannot be channeled and experience multiple scattering in the crystal material. Many of these particles re-enter into the aperture of the machine and have a second encounter on the crystal, usually with much larger impact parameters due to the previous scattering process [3, 4]. The particles may now have the right conditions to be channeled and extracted. Such a process is called multi-pass extraction and if it plays an important role in the overall extraction mechanism, it has strong consequences for the design of an extraction scheme since the machine parameters such as β-function and tune play an essential part in the dynamics of this process. To evaluate the possible contribution of multi-pass extraction was therefore a high priority in our experiments.

2.2 The SPS experiment

For most experiments a 120 GeV coasting beam with an intensity of about $5 \cdot 10^{11}$ protons was used. The lifetime of the beam without external interference can be several hundred hours. The crystal is placed typically about 10 σ from the closed orbit, where only very few halo particles are found initially. The beam is then excited horizontally with band limited white noise induced on a pair of condenser plates. Typical kicks used are of order 0.0005 μrad, but can be varied by changing the noise amplitudes. The beam size slowly increases and once a continuous flux of particles on the crystal is reached, the crystal angle relative to the beam is changed and the extraction signal is recorded as a function of this alignment angle: a so-called angular scan is performed and the maximum of the scan defines optimum alignment. The extracted particles are deflected by 8.5 mrad in a single stage extraction and are measured in an arrangement of detectors described in refs. [5, 6].

3 FIRST RESULTS

The first experiments were performed with crystals in a "bridge" type bending device [5]. Signals from extracted protons were immediately obtained, indicating no problems finding the correct alignment angle. Angular scans were performed and an example is shown in Fig.1 together with profiles measured in the detectors. A full width half maximum of about 200 μrad was found, much more than expected since pure first-pass channeling should have a width about twice the critical angle which is 13.7 μrad at 120 GeV for the (110) planes of Si. The efficiency, defined as the number of particles extracted divided by the number

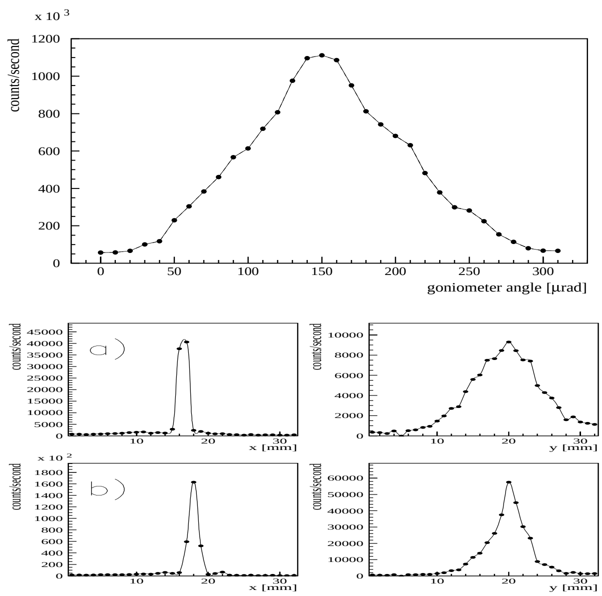

Figure 1: Angular scan with first crystal and extracted beam profiles off (a) and on the (b) maximum.

of particles lost, was about 10 %. Moreover, the profiles showed double peaks when the crystal was not optimally aligned while for the best alignment the peaks were narrow. Both observations can be explained by a significant contribution of multi-pass extraction and a disadvantage of the used bending technique, resulting in an unwanted bending in the vertical plane, so-called ”anti-clastic bending”. Later experiments were done with an improved bending technique, a so-called ”U-shaped” crystal [6], which gave clean signals and efficiencies as high as 18%.

4 MULTI-PASS EXTRACTION

It is experimentally difficult to separate first- and multi-pass channeling. To investigate the possible existence and importance of multi-pass extraction in our experiment, we performed measurement with a special crystal where the surface was covered with an amorphous layer of 30 μm SiO, enough to prevent any first-pass channeling for the impact parameters in our setup which are typically 20 - 50 nm for the initial encounter[4].

4.1 Results with amorphous layer

The crystal with the amorphous layer allows to obtain a clean sample of protons extracted only through the multi-pass process since it prevents any first-pass extraction. When this crystal was used in the SPS, an extracted proton signal was immediately found which was the first direct, model independent evidence for multi pass extraction[3]. It was further found that a substantial extraction efficiency remained in the order of 4-7%, indicating the importance of this mechanism.

4.2 More evidence for multi-pass extraction

Further evidence for the multi-pass extraction came from another observation made with any of the crystals employed: the width of the vertical profiles changed as a function of the alignment angle as shown in Fig.2. It is smallest

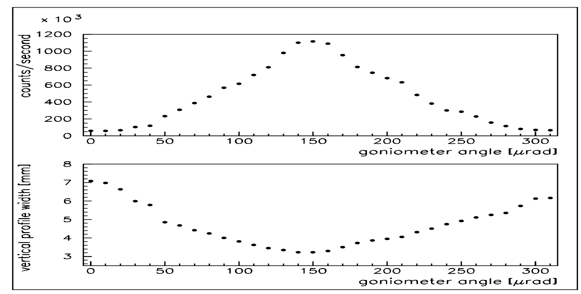

Figure 2: Angular scan and width of vertical profiles

at the best alignment and increases when the crystal is not fully aligned. This can easily be understood in terms of the multi-pass extraction: in the vertical plane the phase space is not confined by the crystalline planes and a larger number of passes implies larger multiple scattering and widening of the profiles. This is clearly demonstrated in Fig.3

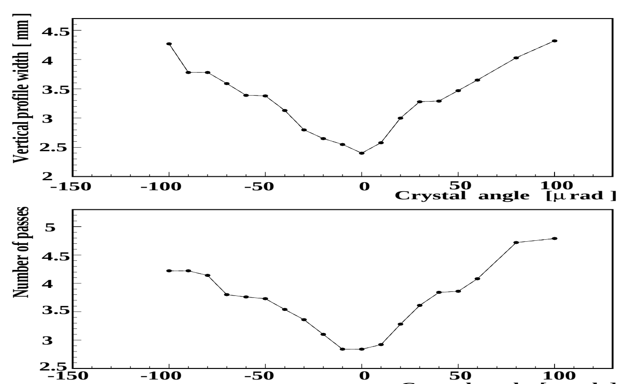

Figure 3: Simulated vertical width and number of passes

where the vertical width obtained from simulation is plotted together with the necessary number of passes through the crystal as a function of the alignment. The correlation and the agreement with the data is excellent and a strong support for our model.

4.3 Implications

The existence and importance of multi-pass extraction has strong implications for future colliders: the initial impact parameters become less important while the machine parameters such as β-function at the crystal are important parameters for the efficiency. Also the collimation scheme should take into account this process.

5 ENERGY DEPENDENCE

To extrapolate the results obtained at 120 GeV to LHC energy, it is important to demonstrate that the model describes the observations correctly over a large energy range, in particular since some of the important parameters such as critical angle ($\propto \; 1/\sqrt{p}$) or dechanneling effects ($\propto \; 1/p$) depend on the beam momentum. In the SPS we had the unique opportunity to extract protons at three energies (14, 120 and 270 GeV) with identical experimental procedures[8]. For all energies, a good signal of extracted protons was observed and compared to the models used in the simulation. The main results are summarized in Fig.4.

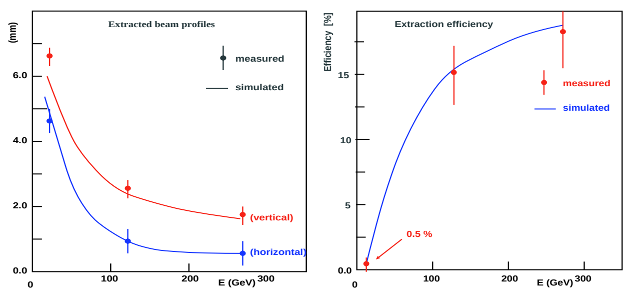

Figure 4: Efficiency and profile widths measured and simulated

The efficiency measured at the three energies is shown together with the prediction from the simulation programme. Unfortunately, the prediction for the efficiency strongly depends on parameters that are not known well enough, e.g. the thickness of the inefficient layer. We have adjusted the simulation to match one of the observed points (120 GeV) to test the energy dependence[8]. As can be seen in Fig.4, the relative efficiencies are reproduced very well. The low efficiency of 0.5% at 14 GeV is due to large multiple scattering and dechanneling. The dechanneling length is only 0.89 cm compared to the crystal length of 4 cm, therefore only about 2% of the initially channeled particles remain channeled. The basic mechanisms leading to extraction and determining the efficiency are well understood and increase the confidence in an extrapolation to LHC energies.

6 EXTRACTION OF HEAVY IONS

With the availability of relativistic Pb ion beams at the SPS it was of interest to test the principles of extraction with this high energy beam. Fully stripped Pb ions (Pb^{82+}) at 22 TeV, corresponding to 270 GeV per nucleon, were stored in the SPS and the usual procedure for extraction was applied [9]. An example of an angular scan and the profiles are shown in Fig.5. The width of the scan is significantly narrower than for protons and one may speculate whether this is due to a suppression of multi-pass extraction which is expected for heavy ions. The measured efficiency is around 10%, slightly lower than for protons with the same crystal at comparable energy per nucleon.

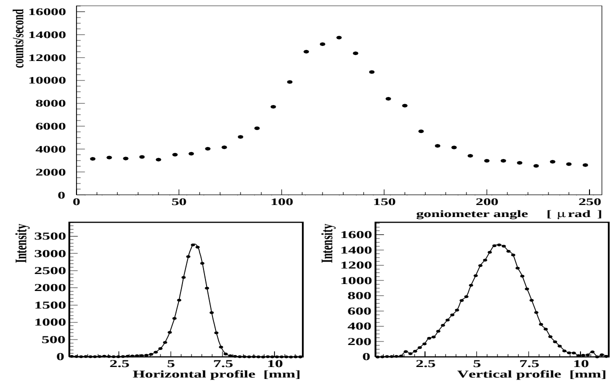

Figure 5: Angular scan and profiles obtained with Pb ions

7 SUMMARY

The main results and observations made in the SPS experiments with bent crystals can be summarized as follows:

- Protons were extracted from the SPS with a bent crystal with good efficiency.
- The bending technique and the crystal quality were found to be important.
- At the energy range of the SPS the multi-pass extraction mechanism plays an important role and must be considered for future design.
- The energy dependence of the crystal extraction process was measured and found to follow the expected behaviour.
- The extraction of heavy ions (fully stripped Pb ions, Pb^{82+}) was demonstrated for the first time.
- An extraction scheme with bent crystals at the LHC seems feasible.

Acknowledgement

We would like to thank all members of the crystal extraction collaboration RD22 for their valuable contributions.

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