EXTRACTION OF 22 TeV/c LEAD IONS FROM THE CERN SPS USING A BENT SILICON CRYSTAL

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1 ABSTRACT

The extraction of protons from the halo of a circulating beam has been repeatedly demonstrated at the SPS. In a recent experiment a coasting lead ion beam was available at a momentum of 270 GeV/c per charge corresponding to a total momentum of 22 TeV/c per ion and the possibility to extract ultrarelativistic lead ions with a bent crystal could be demonstrated for the first time. We present the experimental challenges, the measurements performed during this experiment and the first results.

2 INTRODUCTION

Extraction of high energy protons from a stored beam with a bent crystal has been demonstrated successfully and with a good extraction efficiency at the CERN SPS [1, 2, 3] and other laboratories [4]. At the CERN SPS it was shown that protons could be extracted for a large range of energies between 14 and 270 GeV and the energy dependence is in good agreement with the expectation [5].

More recently [6] fully stripped lead ions $^{208}Pb^{82+}$ were deflected in a bent crystal in a beam line experiment at the SPS with high efficiency. Encouraged by this result and due to the availability of Pb ions in the SPS we have conducted a short experiment where we stored a lead ion beam in the SPS at a momentum of 270 GeV/c per charge, i.e. a total momentum of approximately 22 TeV/c. Using the standard experimental procedure we obtained Pb ions extracted from the coasting beam with a bent crystal. It is the first time that an ion beam at high energy was handled in this way.

In this paper we shall first describe the setting up of the SPS accelerator as a lead storage ring and discuss the experimental difficulties connected with this high energy and charge per nucleon. We present the results obtained and estimate the extraction efficiency.

3 PREPARATION

3.1 Setting up of the SPS for Pb

The fully stripped lead ion beam is injected in the SPS with a momentum of 13 GeV/c per charge in 4 batches (2 x 10^{10} charges/batch) each 2 μs long. The beam is accelerated to a momentum of 26 GeV/c per charge with a fixed-frequency acceleration technique [7], it is debunched to fill the whole machine (23 μs revolution period) to increase the effective spill length for the experiments and then it is further accelerated to 400 GeV/c per charge, the usual energy of lead ions for fixed target physics. Because of the large emittances of the beam (close to the physical acceptance of the machine, in particular vertically) the control of the orbit, of the tune (QH=26.62 and QV=26.58), of the chromaticity (close to zero in both planes) and of the momentum spread is important all through the acceleration and in particular at low energy. In the preparation of this experiment the abovementioned corrections were performed and a single batch was injected and accelerated up to 270 GeV/c per charge where all the ring power converters were frozen and the injection and beam dump kicker inhibited. Due to the low intensity no relevant instabilities are observed.

To obtain the desired emittance growth, transverse noise was applied to the beam as in the case for protons [1, 2, 5].

3.2 Setting up of the experiment

The equipment available for this experiment has been identical to the one described for proton extraction in Refs. [1, 2, 3]. The extracted beam, deflected 8.5 mrad by the bent crystal, exits the vacuum chamber and passes three scintillation counters (used in coincidence). The $^{208}Pb^{82+}$ ions are expected to give a very strong signal in these scintillators, at least two orders of magnitude above the one for protons and pions. Thus, the setting up of the corresponding high voltages (HV) on the photomultipliers was done in the following way: First, the crystal was misaligned (no extraction!) and background was observed in the detectors set to the nominal proton HV (e.g. 2450 Volts in SC1). Then, the HV was lowered until the background signal disappeared (2000 V). Finally, in order not to lose any extracted Pb ion signal, the HV was set 50 Volts higher for data taking. Discriminator levels and delays remained untouched. Angular scans, obtained by turning the crystal and observing the coincidence rate SC1*SC2*SC3, show about 20% of background (cf. Figs. 1 a to c). This is a clear indication that the HV was not perfectly tuned for Pb ions - due to lack of time. For the estimates of the extraction efficiency, the same triple coincidence was used in the "steady state" for a well-aligned crystal, and a 20% background subtraction was applied to the extracted beam rate.

The extracted beam profiles were obtained from the luminescent screen (BTV) installed downstream of SC2. This BTV is a standard SPS beam instrument, equipped with various screens of different sensitivity, which can be chosen remotely. The screens are viewed by a CCD camera, and more choice of sensitivity is available due to its diaphragm and gain. For the present experiment, the sensitivity could be reduced dramatically with respect to proton extraction, and very clean profiles practically free of

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background could be obtained. These are available either directly on TV screens in the SPS control room or in a digitized form, available at 20 ms intervals, for later evaluation. Typical extracted Pb ion beam profiles are shown in Fig. 2.

4 EXPECTATIONS FOR LEAD IONS

The main difference between lead ions and protons is the high mass and charge state. Both have an impact on the interaction of the ions with its environment, in particular with the crystal. Important for the acceptance for channeling is the critical angle ψ_c which scales with $\sqrt{Z/p}$. For a highly charged ion the relevant parameter is the momentum per charge p/Z and therefore the critical angle for ions is equivalent to the angle for protons at the corresponding momentum of 270 GeV/c, i.e. 9.1 μrad. Protons with a momentum of 270 GeV/c have been successfully extracted from the SPS [5].

Furthermore, the dechanneling scales like Z/p, leading to a dechanneling like for protons of equivalent momentum per charge. Similar arguments hold for the multiple scattering in the crystal and its effects, i.e. widening of profiles and increased impact parameters, should be comparable to protons.

However, due to the dependence of the inelastic nuclear cross-section on the atomic mass A: $\sigma_{in} \propto A^{0.71}$, the losses due to inelastic collisions are strongly increased. Worse, the electromagnetic (Weizsaecker-Williams) break-up cross section is very important for such highly charged, fast ions. As a result, we expect a significant decrease of the contribution of multiple pass extraction to our extraction process.

5 RESULTS

5.1 *Angular scans*

The results of three angular scans can be seen in Figs. 1 a to c. The experimental procedure is similar to the one used for extraction of protons [1, 5]. The three angular scans were taken at different times during the experiment to study the reproducibility. While the widths of the angular scans for proton extraction was difficult to reproduce [1, 5], the limited statistic for Pb ions available at present seems to indicate that the reproducibility is better. Furthermore, after the background of 20 to 25 % is subtracted, the full width half maximum (FWHM) of the scans in Figs. 1 a to c is between 45 and 55 μrad, thus significantly narrower than the ones measured for protons between 14 and 270 GeV/c [5]. One may try to speculate whether these narrower angular scans are due to a suppressed contribution of multiple pass extraction to the total extracted rate, or a reduced phase space acceptance for multiple passes.

5.2 *Extracted beam profiles*

Profiles of the extracted beam were measured with a luminescent screen and the CCD camera, and could be digitized and stored. The results can be seen in Fig. 2. The profiles

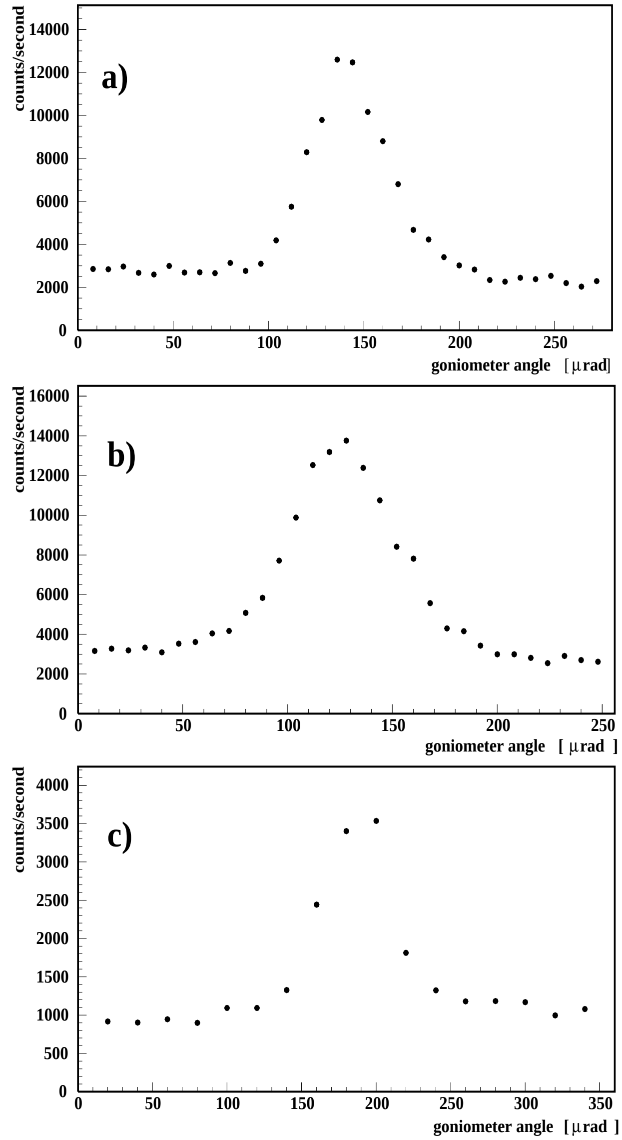

Figure 1: Angular scans, taken at different times to study reproducibility, Pb ions, 270 GeV/c per charge.

are similar to the profiles obtained with the scintillator hodoscope for protons [1, 5].

5.3 *Efficiency*

The efficiency of the extraction process we define as the ratio of the number of extracted particles to the number of particles lost from the circulating beam I_{lost}:

$$\epsilon_{extr} = \frac{I_{extr}}{I_{lost}} \tag{1}$$

The number of extracted ions is determined from a threefold coincidence of trigger scintillation counters SC1*SC2*SC3 and the background estimated from the measured angular scans is subtracted. As mentioned above, the high voltage could not be adjusted to an optimum value

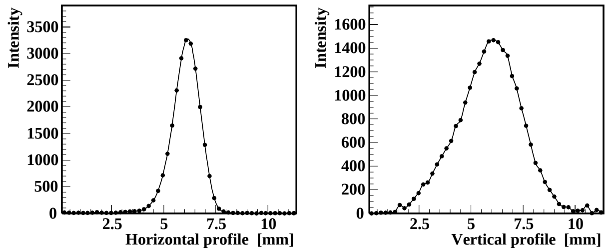

Figure 2: Horizontal and vertical profiles for optimum alignment, Pb ions, 270 GeV/c per charge

for the ions and the error on the number of extracted particles is therefore increased. 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 and thus from the measured beam life time. Due to lack of time, the calibration of both measurements could not be done carefully and the extraction efficiency is therefore less accurate than the ones reported for protons [5]. For the calculation of the efficiency we use rather conservative values and estimate an error on the efficiencies of approximately 35 - 40 %. The results of our efficiency estimates are given in Tab. 1. For the first four measurements in Tab. 1 the standard U-shaped crystal [1, 5], which was used in most of the experiments with protons, was positioned at a distance of about 10 mm from the closed orbit. For the last measurement an alternative crystal with slightly different properties (miscut) was used at a larger distance of approximately 20 mm from the orbit. Significant differences are not observed between the two types of crystals.

Beam intensity (10^7 ions)	Beam lifetime (hrs)	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

Table 1: Extraction efficiences for Pb at 270 GeV/c per charge.

Compared with the measured efficiency from proton extraction at 270 GeV/c which was about 18% [5], the efficiencies for lead are about a factor two smaller, although this comparison is based only on a few measurements made for lead extraction. We show the efficiencies for different values of the noise excitation on the ion beam, i.e. beam lifetimes. As it is the case for protons [1, 5], no clear correlation can be observed and the variation of the efficiencies is even slightly larger than for protons, but with the present precision a clear conclusion cannot be reached.

6 CONCLUSION

We have demonstrated for the first time that fully stripped lead ions ^{208}Pb^{82+} can be extracted from a stored SPS beam at a momentum of 270 GeV/c per charge, corresponding to a total momentum of the ions of approximately 22 TeV/c. Care was taken to suppress possible background signals in the detectors. Although the error on the extraction efficiency is substantially larger than for protons, the estimated efficiency reaches values up to 10%. A first analysis indicates that the width of the angular scans may be significantly smaller than for protons, which can be possibly explained by a reduced angular acceptance and could indicate a suppressed multiple pass component of the extraction process.

7 ACKNOWLEDGEMENT

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