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Strong reduction of the off-momentum halo in crystal assisted collimation of the SPS beam

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ABSTRACT

A study of crystal assisted collimation has been continued at the CERN SPS for different energies of stored beams using 120 GeV/c and 270 GeV/c protons and Pb ions with 270 GeV/c per charge. A bent silicon crystal used as a primary collimator deflected halo particles using channeling and directing them into the tungsten absorber. A strong correlation of the beam losses in the crystal and off-momentum halo intensity measured in the first high dispersion (HD) area downstream was observed. In channeling conditions, the beam loss rate induced by inelastic interactions of particles with nuclei is significantly reduced in comparison with the non-oriented crystal. A maximal reduction of beam losses in the crystal larger than 20 was observed with 270 GeV/c protons. The off-momentum halo intensity measured in the HD area was also strongly reduced in channeling conditions. The reduction coefficient was larger than 7 for the case of Pb ions. A strong loss reduction was also detected in regions of the SPS ring far from the collimation area. It was shown by simulations that the miscut angle between the crystal surface and its crystallographic planes doubled the beam losses in the aligned crystal.

1. Introduction

The experiment UA9 on the study of crystal assisted collimation of the Super Proton Synchrotron (SPS) beam has been started few years ago [1,2]. A bent silicon crystal is used instead of a heavy solid target as a primary collimator deflecting channeled particles and directing them into a secondary collimator–absorber. In this case, particles hit the absorber far from its edge therefore the possibility of their scattering back towards the beam should be considerably reduced. Experiments on crystal assisted collimation have been performed before at the IHEP synchrotron [3], RHIC [4] and Tevatron [5]. The possibility of improving the collimation efficiency of the Large Hadron Collider (LHC) beam halo using a crystal primary collimator has been studied by simulation in [6]. A possible layout for crystal-assisted collimation at the LHC has been considered in [7].

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Fig. 1. (Color online.) The simplified layout of the UA9 experiment. The crystal primary collimator C4 is located upstream the quadrupole QF518 (QF1). The TAL acting as a secondary collimator–absorber is upstream the quadrupole QF 520 (QF2). Some target, SC or RP, in a high dispersion HD area is used to measure off-momentum particles produced in the collimation process. Here QD1 and QD2 are the defocusing quadrupoles.

The experimental studies [1,2] have been performed with 120 GeV/c per charge stored beams of protons and Pb ions. Four bent silicon crystals C1–C4 of 2 mm long with different bend angles (150, 140, 165 and 176 μrad) were separately used as a primary collimator. Two of them, C1 and C4, are strip crystals [8,9] bent along (110) equidistant planes. The crystals C2 and C3 are quasi-mosaic crystals [10] bent along (111) non-equidistant planes. Perfect alignment of the crystals required to deflect particles in channeling regime was found quickly and is very reproducible. The channeling efficiency of halo protons measured by intersecting the deflected beam with another collimator reached 85%.

The beam halo losses due to inelastic nuclear interactions of particles in the aligned crystal were found to be considerably smaller than for its amorphous orientation. The observed loss ratio (reduction) was about 6 for protons and about 3 for Pb ions. Momentums of halo particles leaking out from the collimation station are smaller than the synchronous one due to ionization losses in the crystal and absorber. These particles form the off-momentum halo of the beam. A scan of horizontal positions by a scraper in the first high dispersion (HD) area downstream of the absorber showed a significant reduction of the off-momentum tail of the beam for the aligned crystal.

However, the predictions made by simulation give loss reduction values larger than 30 for the experiments on the SPS proton beam collimation. The discrepancy of the predictions with the experiments may be mainly caused by the miscut angle between the crystal surface and its crystallographic planes, which was not taken into account in the simulations [2].

In this Letter the experimental results on the crystal assisted collimation are presented for different energies of the SPS stored beam using 120 GeV/c and 270 GeV/c protons and fully stripped $^{208}Pb^{82+}$ ions with 270 GeV/c per charge. The correlation of the beam losses in the crystal and in the HD area downstream where off-momentum particles produced in the collimation can interact with some HD target placed far from the orbit in the absorber shadow has been under study. The analysis of the experimental results was performed by simulation using a model of the crystal with a miscut angle. The beam loss measurements in regions of the SPS ring far from the collimation area have been realized using the multi-bunched beam of protons and Pb ions.

2. The experiment description

Fig. 1 shows the schematic layout of the UA9 experiment in the SPS sector 5. Only the devices used in the measurements described below are shown. The crystal primary collimator and the absorber stations are installed at the SPS azimuths with relative horizontal betatron phase advance close to 90 degrees and with a large value of the horizontal beta function. The first station contained four crystals, which can each be used separately as a primary collimator. The results obtained with the strip silicon crystal C4 produced using the technologies described in [8,9] will be discussed here. The crystal parameters are presented in Table 1. The crystal was mounted in the IHEP goniometer (UA9 devices are described in Ref. [11]), which allows changing the crystal orientation relative to the beam halo direction with an angular accuracy of about ±10 μrad. The second station contains a 60 cm long tungsten absorber (TAL) used as a secondary collimator. The two-sided collimator (COL) was used for the alignment of the UA9 devices relative to the beam orbit.

Table 1
Parameters of Si crystal C4 bent along (110) planes.

Length (mm)	Bend angle α (μrad)	Bend radius R (m)	Miscast angle θ_m (μrad)
2.0	176	11.36	200

Table 2
Relevant accelerator parameters.

Parameter	C4	TAL	SC	RP
β_x (m)	76.156	87.675	90.432	99.033
σ_x (mm)	0.956	1.026	1.042	1.09
$\Delta\mu_x$ from C4 (2π)	0	0.2475	0.4908	0.4951
D_x (m)	−0.7856	-6.4×10^{-4}	3.4015	3.5922

The third station in Fig. 1 with targets limiting the accelerator aperture is in the HD area downstream the collimator–absorber. Off-momentum particles with sufficiently large $\delta = p/p_o - 1 \neq 0$ (p and p_o are momenta of a circulating particle and of the synchronous particle, respectively) produced in the crystal or in the absorber and escaping from the collimation area have large displacements from the orbit here, $x_\delta = D_x\delta$, where D_x is the dispersion function. If we put one of the HD targets at a certain distance from the orbit in the TAL shadow, off-momentum particles will interact with the target and produce secondary particles, which will be detected by the beam loss monitors (BLM) downstream. The signal value of this BLM allows to estimate the off-momentum halo intensity. As the target in the HD area we used a beam scraper SC (a 10 cm long bar of duralumin) and a movable Roman pot (RP) (its 3 cm long stainless steel edge). As beam loss monitors (BLM_1 and BLM_2 in Fig. 1) we used the BLMs developed for LHC [12] with low noise and high sensitivity and the scintillation telescopes [11].

In the SPS, the beams of protons or Pb ions were accelerated to 120 GeV/c or 270 GeV/c per charge with nominal betatron tunes $Q_H = 26.13$ and $Q_V = 26.18$. The average number of particles per bunch was about 1.15×10^{11} for protons and about 1.4×10^{8} for Pb ions. In the case of protons, the measurements in the collimation area and in the HD area were performed with a single bunch beam. The measurements of the beam losses in regions of the SPS ring far from the crystal (the beam loss map measurements) were made with multi-bunched beams of protons and Pb ions. The relevant accelerator parameters at the azimuths of some UA9 elements are listed in Table 2, where β_x is the horizontal beta-function, σ_x is the RMS value of the horizontal beam size (here for the RMS emittance $\varepsilon = 0.012$ μm rad) and $\Delta\mu_x$ is the horizontal phase advance between the elements.

As described in [1,2] at the beginning of each measurement the two-sided collimator COL was centered relative to the closed orbit. The collimator half gap $X_{1/2}$ determined the reference beam envelope. Then the alignment positions for all movable elements were determined by fixing their positions at the edge of the collimator shadow. After the alignment all elements were moved back to their garage positions while the crystal C4 and the TAL were put in the collimation positions. The crystal was moved by Δ_{cr} closer to the beam and the TAL moved by Δ_{tal} further away from the orbit, improving conditions for the multi-turn extraction of halo particles. The gap between the crystal and the TAL $X_{off} = \Delta_{cr} + \Delta_{tal}$ should be carefully selected to optimize the beam collimation efficiency.

3. Experimental results

We first consider the results obtained with an SPS stored beam of 120 GeV/c protons. The horizontal RMS emittance was about $\varepsilon = 0.012$ μm rad and the RMS bunch length $\sigma_t = 0.6$ ns.

In Fig. 2 curves 1 show the dependencies of beam losses observed in the crystal (a) and in the HD area target (b) on the angular position of C4. Two scintillation telescopes were used as beam loss monitors, BLM_1 and BLM_2, respectively. The observed dependences are normalized to the beam intensity and to the loss value for the amorphous orientation of the crystal. The collimation positions of C4 and TAL were $X_{C4} = 4.6$ mm ($4.8\sigma_x$) and $X_{TAL} = 7.2$ mm ($7\sigma_x$). The gap between them at the TAL azimuth was $X_{off} = 2.3$ mm ($2.24\sigma_x$). As a target for the measurement of the off-momentum halo intensity in the HD area, the RP was put at a distance $X_{RP} = 8.93$ mm ($8.2\sigma_x$) from the orbit. The projection of the TAL position to the RP azimuth was $X_{TAL}(RP) = 7.65$ mm. Thus, the RP was in the shadow of the TAL but only for particles with sufficiently small δ.

The dependencies are well correlated. The loss minima are observed at the same crystal angle when most of the particles are deflected due to channeling. Inelastic interactions with the crystal nuclei are practically excluded for channeled particles. This explains the loss minimum in Fig. 2a. The beam losses in the minimum occur mainly due to the non-channeled fraction. We determine the beam loss reduction R_{bl} as the ratio of the losses for the amorphous and channeling orientations. The reduction measured in the crystal area $R_{bl}(C4) = 10$. Off-momentum particles, which can interact with the HD area target, belong to the same non-channeled beam fraction. Their number is also reduced. However, the loss reduction observed in the HD area is smaller, $R_{bl}(HD) = 4.5$. This decrease can occur due to scattering of some particles from the TAL back to the beam.

On the right of the channeling minimum there is the angular region with reduced losses. This is the crystal orientation region where particles are deflected due to volume reflection, which allows them to reach the TAL aperture in a smaller number of passages through the crystal. This explains the loss reduction in the crystal, Fig. 2a. The VR region of reduced losses is also well seen in the HD area, Fig. 2b. However, the reduction is smaller than in the crystal. A possible explanation for that is also scattering of some particles from the TAL back to the beam.

Curves 2 in Fig. 2 show the dependencies of the inelastic interaction number in the crystal (a) and in the RP (b) obtained by simulation based on the model described in [13] taking into account synchrotron oscillations of particles. In contrast with the previous simulation the crystal model takes into account the miscut angle θ_m between the crystal surface and the (110) crystallographic planes. Fig. 3 shows the situations when the primary crystal collimator has $\theta_m = 0$ (a) and $\theta_m \neq 0$ (b). In both cases the crystal planes at its entrance face AC are parallel to the beam envelope (the dashed line touching the crystal on the left). The crystal touches the beam envelope at the point A of its entrance face in the case (a) and at the point B of its exit face in the case (b). As a result, a particle with the same impact parameter b enters the crystal from its entrance face and is captured into channeling in

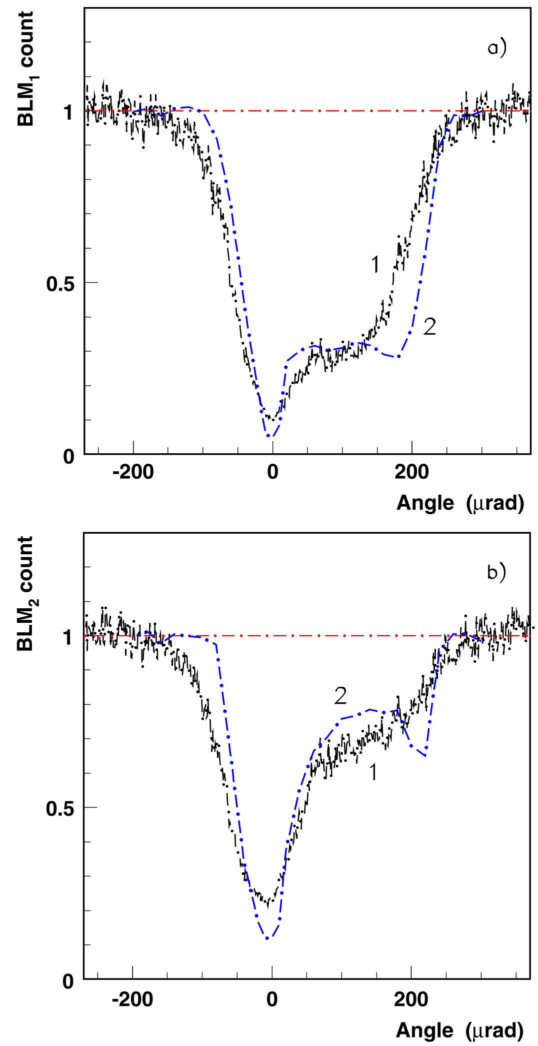

Fig. 2. (Color online.) Beam of 120 GeV/c protons. Curves (1) are the dependencies of beam losses observed in the crystal (a) and in the HD area target (b) on the angular position of the crystal C4 normalized to its value for the amorphous orientation of the crystal (dot-dashed line). The scintillation telescopes B-L and J-K were used as BLM_1 in (a) and BLM_2 in (b), respectively. (2) The dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by simulation with taking into account the crystal miscut.

the case (a) and enters through its side face with a large angle to the bent planes and traverses the crystal acting as an amorphous material in the case (b). In the last case a particle acquiring some amplitude increase due to multiple scattering can enter the crystal next time during the following turns through its entrance face AC and be captured into channeling. However, some particles entering through the side face at the first passage will be lost due to inelastic interactions. These losses are additional in comparison with the case (a). Thus, the beam loss reduction in channeling R_{bl} for the real crystal with a miscut angle should be smaller.

The decrease of R_{bl} due to the crystal miscut depends on the ratio between the impact parameter values in the first hits and the projection value of the crystal side face Δ (see Fig. 3). In our case $\Delta = R(\cos(\theta_m - \alpha) - \cos\theta_m) = 0.224$ μm, where R and α are the crystal bend radius and angle (see Table 1). In the experiment the time required to repopulate the halo scraped by the TAL near the crystal distance from the orbit was measured. This gave the average rate of the oscillation amplitude growth as $\lambda = 2.2$ μm/s. According to our simulation the average impact parameter of particles with the crystal at this rate is $b = 0.28$ μm (the full width of

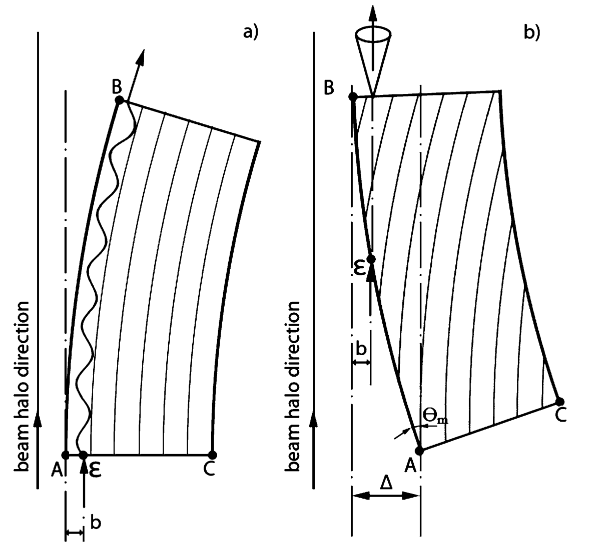

Fig. 3. (Color online.) The crystal primary collimator with the miscut angle $\theta_m = 0$ (a) and $\theta_m \neq 0$ (b). For (a) the first hits of halo particles occur with the entrance face AC, where particles are captured in channeling regime and deflected. For (b) the first hits occur with the side crystal face AB, where all particles pass the crystal as amorphous substance and can have inelastic interactions with the crystal nuclei.

the impact parameter distribution is about 1 μm) and the crystal miscut more than doubles the beam losses at perfect alignment. The beam loss reduction obtained by simulation for C4 with taking into account its miscut $R_{bl} = 21$. Thus, the discrepancy with the experiment became considerably smaller. The beam loss level for the VR region is in good agreement with the experiment. The dependence of beam losses in the RP obtained by simulation is in satisfactory agreement with the experiment (Fig. 2b). The loss reduction is also about twice larger than the experimental value, $R_{bl}(\mathrm{HD}) = 8.4$.

It should be noted that while the crystal miscut changes considerably the beam losses in the aligned crystal, it changes very little the channeling efficiency that is the halo fraction deflected by the bend angle. For our conditions according to simulation, the channeling efficiency at perfect alignment is $P_{ch} = 93.2\%$ and 91.4% for the case (a) and (b) shown in Fig. 3, respectively.

Let us note also that the RP was installed too close to the orbit in this collimation experiment. It was in the shadow of the TAL and the crystal but not for the whole halo. The halo particles with large momentum deviations $\delta > 10^{-3}$ could first hit the RP. According to simulation the contribution of such particles is about 5%. The collimation process was disturbed for them and they produced the background level of losses in the RP. This of course reduced the values of the beam loss reduction observed both in the crystal and in the HD area. The target to probe the off-momentum halo should be put in the shadow of the crystal for all particles of the bunched beam; that is in our case the RP distance from the orbit should be $X_{RP} > X_{C4}(\beta_{RP}/\beta_{C4})^{1/2} + D_x\delta_h = 11$ mm, where $\delta_h = 1.615 \times 10^{-3}$ is a bucket half-height.

Similar experiments on crystal collimation were performed with the SPS beam of 270 GeV/c protons. The horizontal RMS emittance was $\varepsilon = 0.005$ μm rad and the RMS bunch length $\sigma_t = 0.55$ ns. It should be noted that the crystal channeling characteristics were changed by changing the particle energy. The critical channeling and volume reflection angles, $\theta_c, \theta_{VR} \sim p^{-1/2}$, decreased by a factor of 1.5 and the angle of multiple Coulomb scattering $\theta_{ms} \sim p^{-1}$ decreased by a factor of 2.25. Decreasing particle scattering should require a larger number of passages thorough the non-oriented crystal to reach the TAL aperture. This causes growth

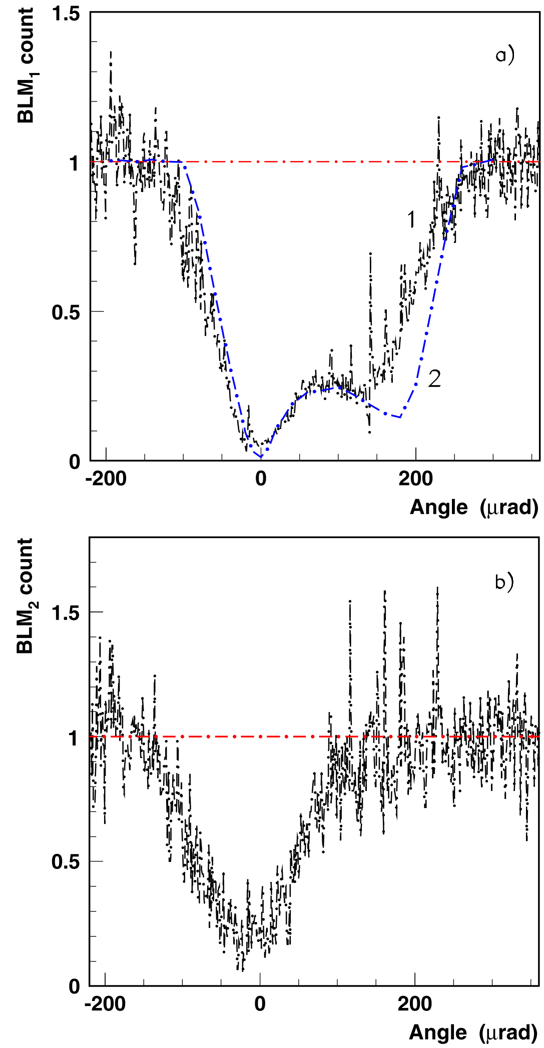

Fig. 4. (Color online.) Beam of 270 GeV/c protons. The same as in Fig. 2. The BLMs developed for LHC were used as BLM_1 in (a) and BLM_2 in (b), respectively.

of the beam losses and consequently the loss reduction R_{bl} should increase.

In Fig. 4 curves 1 show the dependencies of beam losses observed in the crystal (a) and in the HD area target (b) on the angular position of C4. The crystal and the TAL collimation positions were $X_{C4} = 5.6$ mm ($9\sigma_x$) and $X_{TAL} = 8.92$ mm ($13.5\sigma_x$). The gap between them at the TAL azimuth was therefore $X_{off} = 2.89$ mm ($4.4\sigma_x$). It is larger than for the case considered above with 120 GeV/c protons. Here the measured beam loss reduction in the aligned crystal $R_{bl} = 20$. This R_{bl} value is considerably larger than for 120 GeV/c protons, which is probably caused by the larger gap and by smaller angular kicks of multiple scattering. Both these factors lead to a beam loss increase for the amorphous crystal orientation, which increases R_{bl}. The second minimum in the VR region caused by the amplitude drift due to volume reflections and described in [1] is clearly seen in the experimental dependence. Simulation (curve 2 in Fig. 4a) well describes the loss dependence character in the crystal and its level in the VR region.

The aluminum scraper was used as the HD area target. It was put far from the orbit, $X_{sc} = 41$ mm, to avoid disturbance of the collimation. The crystal angular position corresponding to the beam loss minimum in the scraper (Fig. 4b) is the same as for the crystal. Here the beam loss reduction $R_{bl}(\mathrm{HD}) = 6$. The

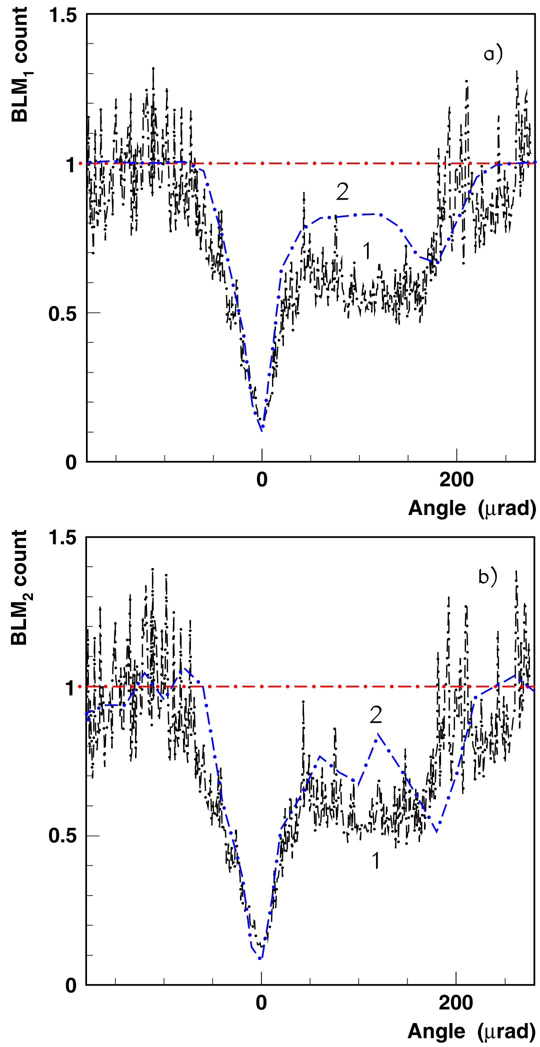

Fig. 5. (Color online.) Beam of Pb ions with 270 GeV/c per charge. The same as in Fig. 2. The B and J scintillation detectors were used as BLM$_1$ in (a) and BLM$_2$ in (b), respectively.

loss reduction in the VR area is visible but considerably smaller than for the case of 120 GeV/c protons. A possible reason is more frequent scattering of protons from the TAL back to the beam because of smaller impact parameters caused by smaller angular kicks acquired in the crystal, that is the TAL contribution to the off-momentum halo generation is larger.

Experiments on the crystal collimation of the SPS stored beam of Pb ions with 270 GeV/c per charge were also carried out. The horizontal RMS emittance was $\varepsilon = 0.011$ μm rad and the RMS bunch length $\sigma_t = 0.55$ ns. The crystal channeling characteristics are determined by the ratio of $p_z = p/Z$ and they are the same for protons and Pb ions with the same p_z. However, their interactions with a crystal are considerably different. As noted in [2] the difference is caused by considerably larger ionization losses, which are proportional to Z^2. Their average value in a 2 mm long silicon crystal for the considered energy is about 7 GeV. This causes a strong orbit shift and, as a consequence, a strong increase of oscillation amplitudes. Three passages of Pb ions through the crystal cause their debunching. Besides, the beam attenuation cross-section in a silicon crystal for Pb ions is more than 10 times larger than for protons $\sigma_{tot} = \sigma_h + \sigma_{ed} = 4.35 + 1.37 = 5.72b$, where σ_h and σ_{ed} are the contributions from inelastic nuclear interactions and electromagnetic dissociation, respectively [14–16]. The attenuation length is about 3.5 cm.

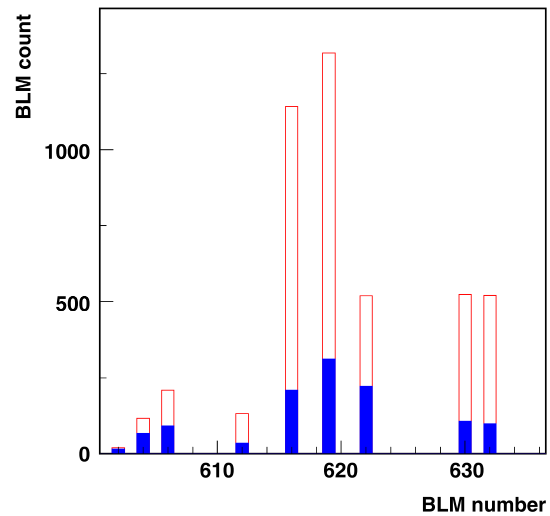

Fig. 6. (Color online.) The beam loss map in the SPS sector 6 for the amorphous and channeling (the histogram filled by blue) orientations of the crystal.

Curves 1 in Fig. 5 show the dependencies of beam losses in the crystal (a) and in the HD area target (b) on the crystal orientation. The collimation positions of the crystal and the TAL were $X_{C4} = 3.1$ mm $(3.4\sigma_x)$ and $X_{TAL} = 6.9$ mm $(7\sigma_x)$. The gap between them at the TAL azimuth was $X_{off} = 3.56$ mm $(3.6\sigma_x)$. The RP, used again as a target, was installed at the distance $X_{RP} = 35.7$ mm. A remarkable similarity of the beam loss dependencies in the crystal and in the RP is observed. The loss reduction at the channeling orientation is larger than 7 in both cases. This is evidence that the TAL contribution to the formation of the off-momentum halo is negligible because practically all Pb ions should be lost in the TAL due to inelastic nuclear interactions.

Curves 2 show the simulation results. They describe sufficiently well the experiment near the channeling minimum. The calculated values of the beam loss reduction in the crystal and in the RP are $R_{bl} = 10$ and 12, respectively. They are considerably closer to the experimental results than the considered measurements with protons. However, for the VR angular orientations of the crystal our simulation gives larger losses than the experiment.

Similar measurements using the stored beam of Pb ions were performed with different gap values X_{off} between the crystal and the TAL. They showed the existence of an optimum near $X_{off} = 3.5$ mm. This optimal gap is larger than for protons, which should be caused by a large amplitude increase of ions due to ionization losses in the crystal. Therefore, the gap X_{off} should be large to realize the possibility for particles to be captured in channeling during the subsequent passages after the first unsuccessful passages through the crystal.

The stored multi-bunched beam has been set up for protons (train of 48 bunches spaced by 25 ns) and Pb ions (8 bunches spaced by 125 ns) with 270 GeV/c per charge to provide a possibility for the beam loss measurements in regions of the SPS ring far from the crystal where the sensitivity of the BLMs is not sufficient for the single bunch beam. Fig. 6 shows the beam losses detected by the BLMs located near the main quadrupoles spaced by 32 m in the SPS sector 6, which is 1 km downstream of the crystal, for two crystal orientations corresponding to channeling and amorphous modes in the case of the multi-bunched beam of protons. The losses for the channeling orientation are few times smaller than for the amorphous one.

4. Conclusions

The experimental results on crystal assisted collimation of the SPS beam show a strong correlation of beam losses in the crystal and in the first high dispersion area downstream where the surviving off-momentum halo was probed with a target. The observed beam loss reduction in the aligned crystal was more than 20 for the beam of 270 GeV/c protons. A maximal reduction for the off-momentum halo intensity in the HD area was above 7 observed for Pb ions.

The loss dependencies in the crystal and in the HD area target differ because of a contribution of particle scattering from the TAL back to the beam. The contribution is significant for protons and small for Pb ions because of stronger losses in the TAL due to considerably larger cross-sections of inelastic nuclear interactions and electromagnetic dissociation.

Simulation performed taking into account the miscut angle between the crystal surface and crystallographic planes allowed to improve predictions for the beam loss reduction in the aligned crystal. According to simulation the miscut of the tested crystal more than doubles the loss reduction.

The experiments, especially with Pb ions, showed that there is an optimal gap between the crystal and absorber for collimation. The lowest level of the off-momentum halo intensity measured in the HD area for the channeling orientation of the crystal should be a criterion in search of the optimal gap.

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