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CRYSTAL DEFLECTOR FOR RELATIVISTIC ION COLLIDERS

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Кристаллический дефлектор для коллайдеров релятивистских ионов

Предложено использовать кристаллический дефлектор для вывода релятивистских ионов из гало пучка в проектируемых и сооружаемых коллайдерах релятивистских ионов (RHIC, LHC, Супернуклотрон и других) с энергиями в десятки ГэВ/нуклон и выше. Сделаны оценки эффективности отклонения ядер золота с энергией 100 ГэВ/нуклон для проектных параметров пучка RHIC. Показано, что научная программа этих ускорительных комплексов, обеспечивающих уникальные пучки релятивистских ионов, может быть дополнена экспериментами с фиксированной мишенью.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Crystal Deflector for Relativistic Ion Colliders

Extracted ion beams for fixed target experiments can be provided as a "by-product" at unique multi-GeV ion colliders by means of bent crystal channeling. The main questions in this connection are discussed. Results on efficiency of ion beam deflection and extraction are presented. Calculations on a possible extracted 100-GeV, Au-beam parameters for RHIC were made.

The investigation has been performed at the Laboratory of High Energies, JINR.

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I. Introduction

The experiments performed for the first time at the 10 GeV Dubna synchrophasotron [1] and then at the 70 GeV proton synchrotron at Protvino (USSR)[2] have shown that bent crystals can be successfully used at high energy accelerators for proton beam extraction. The proposals of using crystal deflectors for particle extraction from beam halo at the largest proton colliders SSC (USA)[3] and LHC(CERN)[4] have been formulated, and appropriate systems are under investigation now. In this connection test runs at Tevatron and SPS beams are scheduled [5,6]. The most important feature of such an extraction system is that the colliding mode of machine operation is not disturbed, and an additional opportunity to carry out some fixed target experiments simultaneously can be realized.

The expected efficiency of such an extraction system for SSC (the energy of accelerated protons is about 20 TeV) can reach approximately 97%[7]. Only a few percent of particles incident on a deflector are lost due to nuclear interactions or large angle scattering. Such a high efficiency is determined by a small angular beam divergency at the point of extraction: $\overline{\theta}_x \ll \theta_c$ (θ_c is a critical angle for particle capture in the planar channeling regime) and by the possibility of multiple passages of particles through the deflector.

The experiments with carbon nuclei at an energy of 3.5 GeV/u performed at the Dubna synchrophasotron have shown that relativistic nuclei can be also deflected by bent crystals[8].

It would be interesting to realize in a similar way nuclear beam extraction for fixed target experiments at the biggest nuclear colliders RHIC and LHC which are under construction now. This additional opportunity to extend an experimental program is also important for the other high energy colliders which are under design at GSI(Darmstadt)[9] and LHE(Dubna) [10].

Our calculations of the efficiency of ion beam extraction by bent crystals and main questions concerning the above-mentioned problem are presented below.

2. Efficiency of Ion Beam Deflection

Let us consider the variation of main parameters of particle channeling in crystals in going from protons ($Z=1$; $E=E_1$) to multicharged ions ($Z=Z$, $E=AE_1$, A-atomic number). Charge and energetic dependencies of channeling parameters were discussed in [11]. Assume that the ion energy per nucleon E_1 is just the same for the proton case (i.e. the velocity β and the Lotentz-factor of ion γ remain the same as for the proton), but the charge and the total energy of channeling particle are different.

High energy charged particles can be deflected by bent crystals if the radius of their curvature R will be larger than some critical quantity R_c, which value depends on a maximum internal electric field averaged over the crystal atomic planes, $\mathcal{E}_{max}$[12],

$$R_c(Z, AE_1) = \omega R_c^1 (E_1),$$
$$\omega = \frac{A}{Z}, \quad R_c^1 (E_1) = \frac{E_1 \beta^2}{e\,\mathcal{E}_{max}} \quad (1)$$

As $\omega = 1$ for protons and $\omega \geqslant 2$ for ions, the critical radius for ion channeling should be twice as larger than for protons. It will be convenient to use a new variable $r = R/R_c$ (relative crystal curvature). The effective potential which affects the particle in a bent planar channel is similar (at the same r) to the potential for protons U_{ef}^1:

$$U_{ef}(x,r;\, Z,\, AE_1) = ZU_{ef}^1(x,r;\, E_1) ,$$
$$U_{ef}^1 (x,r;\, E_1) = U^1(x) + \frac{E_1 \beta^2}{rR_c^1} x , \quad (2)$$

where $U^1(x)$ is the planar potential for protons in a straight crystal.

So, just the same dependence of the main channeling parameters on ω takes place for bent crystals as for unbent ones.

Critical transverse energy for stable trajectories of channeling particles is proportional to the charge of nuclei:

$$E_{xc}(r;\, Z,\, AE_1) = ZE_{xc}^1(r;\, E_1) ,$$
$$E_{xc}^1(r;\, E_1) = U_{ef}^1(x_c,\, r;\, E_1) , \quad (3)$$

where x_c is the critical distance for closest approach to a channel wall for channeling particles.

The value of x_c depends on a crystal temperature. We assume $x_c \simeq u_1$, where u_1 is rms amplitude of thermal vibrations of atoms.

The corresponding critical angle of particles relative to the atomic planes in the crystal is the following:

$$\theta_c(r;\, Z,\, AE_1) = \omega^{-1/2} \cdot \theta_c^1(r;\, E_1) ,$$
$$\theta_c^1(r;\, E_1) = \left(\frac{2E_{xc}^1(r;\, E_1)}{E_1 \beta^2} \right)^{1/2} . \quad (4)$$

Let the beam enters the crystal parallel to the bent atomic planes and its angular distribution is Gaussian. Suppose also that the standard angular deviation of particles in the beam $\bar{\theta}_x$ measures in the critical angles $\bar{\theta}_x = \kappa\theta_c$ and it does not change at the considered transition. Then for the particle capture probability into the channeling states we have

$$P_c(r,k;\, z,AE_1) = P_c(r,k;\, E_1) = \frac{1}{d_p}\int_{x_{cr}}^{x_{ch}} \mathrm{Erf}\left[\frac{1}{\sqrt{2}\,k}\left(1-\frac{U^1_{ef}(x_o;r)}{E^1_{xc}(r)}\right)^{1/2}\right]dx_o\,, \qquad (5)$$

where d_p is the channel width, x_{ch} is determined by the equation $U^1_{eff}(x_{ch}) = E^1_{xc}$. It is a universal function for all sorts of particles. The initial distribution of captured particles in the transverse energy $\varepsilon_{xo} = E_{xo}/E_{xc}$ is determined as

$$P_c(\varepsilon_{xo}) = A_c\int_{x_1(\varepsilon_{xo})}^{x_2(\varepsilon_{xo})} \exp\left[-\frac{1}{2k^2}\left(\varepsilon_{xo}-\frac{U^1_{ef}(x_o;r)}{E^1_{xc}(r)}\right)\right]dx_o\,. \qquad (6)$$

Here x_1, x_2 are calculated from the equation $U^1_{eff}(x,r) = E_{xo}$ and A_c is a constant determined by the normalization condition $\int_0^1 P(\varepsilon_{xo})\,d\varepsilon_{xo} = 1$.

Multiple scattering of channeled particles by electrons and nuclei in the crystal is the process, which decreases the efficiency of a crystal deflector. The mean square of the deflection angle of the particle per unit path length due to multiple scattering averaged over the trajectories and the ensemble of channeled particles with the same assumption about the beam divergence (neglecting a weak logarithmic dependence for the electron term) can be written as:

$$\left\langle\frac{\Delta\overline{\theta_x^2}}{\Delta s}\right\rangle(Z,\, AE_1) = \omega^{-2}\left\langle\frac{\Delta\overline{\theta_x^2}}{\Delta s}\right\rangle^1(E_1)\,. \qquad (7)$$

Finally the dechanneling length increases for nuclei as

$$S_{1/2}(r;\, Z,\, AE_1) = \omega\, S^1_{1/2}(r;\, E_1)\,,$$

$$S^1_{1/2}(r;\, E_1) = \frac{E^1_{xc}(r;E_1)}{A^1(r;E_1)}\,, \quad A^1(r;E_1) = \frac{E_1\beta^2}{2}\left\langle\frac{\Delta\overline{\theta_x^2}}{\Delta s}\right\rangle^1. \qquad (8)$$

The deflection efficiency of relativistic nuclei beam at a required angle α can be estimated as follows [13]. This estimate is good enough for the crystal length smaller than the dechanneling length

$$P_d(\alpha;\, r,k) = P_c(r,k)\cdot\exp\left[-\frac{\alpha r R_c(Z,\, AE_1)}{S_{1/e}(r;Z,AE_1)}\right] = P_c(r,k)\cdot\exp\left[-\alpha r R^1_c \,/\, S_{1/e}(r;\, E_1)\right]. \qquad (9)$$

At the same r and k the probability for particles to be in the channeling regime (exponential factor) does not depend on ω and the deflection efficiency is a universal function for protons and nuclei.

Figure 1 shows the capture probability into the channeling regime by a silicon crystal which is bent along (110) planes and the beam deflection efficiency at the angle $\alpha = 1$ mrad as a function of the relative crystal curvature r (a) and the relative beam divergence k (b).

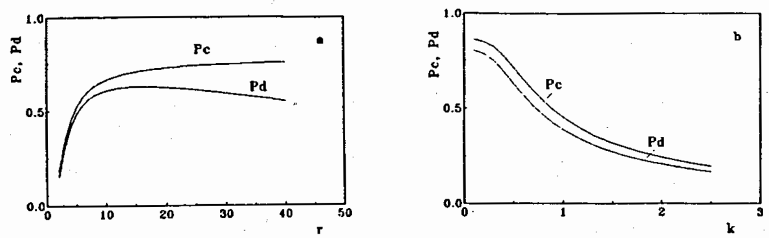

Fig.1. The capture probability into the channeling regime P_c and the deflection efficiency P_d at the angle α = 1 mrad for ultrarelativistic ion beam by a Si crystal bent along (110) planes as a function of the relative crystal curvature r(a) and the relative beam divergence k (b).
(a) k = 0.5; (b) r = 16, optimal bend radius.
The dependences are universal in the relation of a particle energy and charge for the short crystals with length $S \ll S_d$.

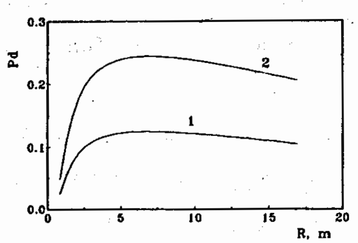

Fig.2. The deflection efficiency by a Si crystal bent along (110) planes for A^{+74} ions with energy of 100 GeV/u at the angle α = 1 mrad versus the bend radius R.
(1) at β_x = 100 m , (2) β_x = 400 m.

3. Efficiency of Ion Beam Extraction

A natural growth of beam halo in ion colliders due to strong intrabeam scattering can provide a flow of particles through a thin crystal deflector installed at some distance from the design particle orbit. To evaluate a possible intensity of an extracted beam, we suppose a Gaussian distribution of particles in the circulating beam. The standard spatial and angular deviations of particles in this case are written as:

$$\bar{x} = \left(\frac{\beta_x \varepsilon}{\pi\gamma}\right)^{1/2}, \qquad \bar{x}' = \frac{\bar{x}}{\beta_x}, \tag{10}$$

where β_x is a betatron function, ε is an invariant emittance. For RHIC parameters [14] (ε = = 22π mm·mrad, Au ions) one can get $\bar{x}$ = 4.52 mm, $\bar{x}'$ = 45.2 μrad and $\bar{x}$ = 9.04 mm, $\bar{x}'$ = 22.6 μrad if the values of the β_x-function are equal to 100 m and 400 m, respectively.

The calculated dependence of the deflection efficiency for Au ions (Z = 74) with an energy 100 GeV/u at the angle α = 1 mrad upon the bend radius of a Si crystal bent along (110) plane are shown at Fig.2. The calculations were made for the beam divergencies which correspond to the two values of the β_x -function. The critical angle of channeling in the unbent crystal for this case is θ_c = 13.5 μrad, and about 15% and 30% of incident particles will be captured in the channeling regime. The maximum deflection efficiency exceeds 10% at the crystal bend radius of 6 m. The appropriate optimum length of the crystal S = αR is about 1 cm. Increasing the crystal length under the same curvature leads to a rapid growth of dechanneled particles number because the dechanneling length is 4 cm for this case.

Due to the A-dependence of inelastic nuclear cross-section $\sigma_{in} \sim A^{0.71}$, a significant decrease of unchanneled fraction will take place in the case of ion beam passage through the deflector. For this reason the efficiency increase of the beam extraction due to multiple passages of particles through the crystal deflector, which can be obtained for high energy protons beam will be substantially suppressed in the case of heavy ion ones. In the case of multiple passages the efficiency of particle extraction can be estimated as

$$P_{ex} = P_d \sum_{n=0}^{N} q^n \simeq P_d \frac{1}{1-q} \quad , \qquad (11)$$

$$q = (1 - P_d)\cdot(1 - P_n) \quad ,$$

where P_n is the probability of decreasing the unchanneled beam fraction in the deflector. For the deflection of Au ions by a silicon crystal at an angle of 1 mrad, the parameters in (11) are: $P_n = 0.6$, $P_d = 0.12$, $q = 0.36$ (for $\beta_x = 100$m), and so the extraction efficiency increases up to 20%.

This estimate is somewhat larger than the real one because equation (11) does not take into account a broadening of the unchanneled beam fraction due to multiple scattering at the deflector which will lead to additional loss of particles at the walls of the beam pipe. This can be corrected by adding one more similar multiplier to the expression for q in (11).

To estimate the fraction of particles passing through the crystal deflector placed at the distance x_{bc} from the equilibrium orbit, the following expression may be used:

$$P_{en}(x_{bc}) = \int_{x_{bc}}^{x_{bc}+\Delta x_{bc}} P(x)\,dx = \frac{1}{2}\left[\mathrm{Erf}\left(\frac{x_{bc}+\Delta x_{bc}}{\sqrt{2}\,\bar{x}}\right) - \mathrm{Erf}\left(\frac{x_{bc}}{\sqrt{2}\,\bar{x}}\right)\right] , \qquad (12)$$

where x_{bc} is the deflector thickness.

Intrabeam scattering leads to increasing the ion beam dimensions. The emittance of the Au ion beam at the final energy ($\gamma = 100$) becomes three times larger than at the beginning after ten hours of particle storage regime in the RHIC [15]. This effect manifests itself especially at the beginning stage. The fraction of particles entering the deflector during the time interval Δt due to emittance growth can be expressed as:

$$\Delta P_{en}(\Delta t) = P_{en}(\varepsilon(t+\Delta t)) - P_{en}(\varepsilon(t)) \quad . \qquad (13)$$

The average intensity of the beam entering the deflector can be written as

$$n_{en} = N_o \, \Delta P_{en} / \Delta t$$

and the extracted beam intensity:

$$n_{ex} = n_{en} \cdot P_{ex} \quad ,$$

where N_o is the total number of stored ions. So, our calculations show that it is possible to provide an extracted beam of gold ions with intensity $n_{ex} \approx 10^2 s^{-1}$ by means of a bent crystal $\Delta x_{bc} = 1$ mm thickness installed inside the RHIC vacuum chamber (7.29 cm in inner diam) at the distance $x_{bC} = 15$ mm from the equilibrium orbit and at the azimuth with $\beta_x = 100$ m (so that $x_{bC} > 3\bar{x}$). The extracted beam intensity can be several times larger if we increase the deflector thickness and remove it to the azimuth where $\beta_x = \beta_{max} = 400$ m.

The level of external beam intensity ($n_{ex} = 10^2 \div 10^3 \, s^{-1}$) is already enough for experiments with nuclear plastic track detectors and photoemulsions. The typical value of particle track density for plastic is $n \approx 10^3$ cm^{-2}, and the stack dimension is 10 x 10 cm^2 [16]. Taking into account that the cross section of the deflector is about 0.1 cm^2 and the extracted beam divergence is also small (θ_c), one can use the corresponding step by step movement of a detector unit or beam scanning to provide quasi-uniform irradiation of the detector area under above mentioned particle density.

Experimental conditions for an exposure of emulsion stacks are similar, but the particle track density can be increased up to $2 \cdot 10^4 cm^{-2}$.

The extracted beam intensity can increase substantially (up to 10^4-10^5 s^{-1}) using a special mechanism of beam halo particles shifting at the deflector.

External low intensity ion beams provided as a "by-product" at unique high energy ion colliders can be also used for the calibration of experimental instrumentation and even for some applied investigations (local radiation damage of different materials or, e.g., electronics components).

So the addition of crystal deflectors to the lattice of relativistic ion colliders with energies of tens GeV and higher will open up new possibilities for experiments and involve more users in their scientific programs.

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