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Perspectives and plans for HERA

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Résumé - Dans les anneaux de stockage à collision d'électrons et de protons "HERA", il est nécessaire que les électrons soient polarisés longitudinalement au moment de la collision. L'hélicité doit pouvoir être positive ou négative au choix. A l'entrée de la zone d'interaction, un rotateur de spin fait pivoter le spin de sa position verticale initiale dans l'axe longitudinal du faisceau, soit dans le même sens soit dans le sens inverse à celui de la direction des particules, et à la sortie de la zone d'interaction, un deuxième rotateur de spin le ramène à la position verticale. Les rotateurs de spin utilisés à cet effet sont d'un type nouveau permettant d'obtenir une déflexion et un écartement du faisceau relativement faibles (mini-rotateur). Ils avaient d'abord été conçus pour une géométrie de croisement à 20 mrad et ils ont maintenant été adaptés pour la nouvelle géométrie de collision frontale qui a été adoptée pour HERA.

Abstract - In the HERA ep collider, longitudinal electron polarization with the choice of both helicities is required at collision. A pair of spin rotators turns the spin from its vertical orientation in the arc into either the forward or the backward longitudinal direction at the interaction point, and then back into the vertical again. The spin rotators are of a new kind with relatively small bending and beam excursion (mini rotators). Originally proposed for the former 20 mrad crossing geometry, they are now being matched into the new head-on collision geometry that has recently been adopted for HERA.

The HERA experiments require well defined electron helicities. Four pairs of spin rotators will therefore be employed to turn the transverse electron spin into the beam direction at each of the 4 interaction points. For this purpose, a new type of spin rotator, the so-called mini rotator proposed in 1983 /1,2/, was recently adopted.

In principle, this spin rotator derives from a Siberian Snake that was found several years ago /3/ and consists of a vertical and a horizontal matched beam bump which are folded into each other and start and end with a $\pm 45^\circ$ spin rotation each (see Fig. 1). This snake would rotate the spin by 90° about the longitudinal axis. It transforms into the rotator by inverting the sign of the last bending magnet; this changes the outgoing spin orientation by $2 \times 45^\circ$ and makes it come out longitudinal instead of transverse horizontal. The rotator, then, is not a straight unit as the snake was, but bends the beam in the horizontal plane by an angle corresponding to 90° spin rotation. This bend can be incorporated into the arc of the ring by making the rotator an integral part of it.

Fig.1: Principal sketch of mini rotator as obtained from a Siberian Snake of the 1st kind.

In practice, the spin rotation angles in this type of rotator may be chosen different from the scheme in Fig. 1. When assuming the vertical beam bump in the rotator to be symmetric, and applying the geometric boundary conditions as overall length, bending angle etc., there still is a two-dimensional variety of rotator parameters to be chosen from. J. Buon has done a systematic investigation of this variety /4/, but before looking at his results, we must explain some of the rotator's properties.

The rotator is laid out for a certain energy at which it simultaneously provides the correct geometry and spin rotation. For given magnet strength, the beam deflection varies inversely with energy, while the spin rotation is independent of energy. Therefore, when varying the beam energy in the rotator, one can either maintain the correct beam geometry, by scaling the magnet strengths with energy, or maintain the correct spin rotations, by keeping the magnet strengths constant. Since the rotator is an integral part of the horizontal ring geometry, we must scale the horizontal magnet strengths when changing the energy of the ring, but we can then use the amplitude of the vertical beam bump in the rotator as a free parameter for compensating the induced error in spin rotation /2/. The analysis shows that this is a practicable way to extend the range of rotator operation to plusminus a few percent about its design energy. We believe this energy range to be necessary in tuning the ring for maximum polarization. A similar correction, more effective, consists in superimposing a certain small horizontal beam bump on the rotator /5/. The efficiency of these corrections is one of the criteria for choosing the rotator parameters.

Another criterion for rotator evaluation is its spin tune shift and the variation of this tune shift with energy. In general, the rotator not only turns the equilibrium spin direction from the vertical into the longitudinal and back into the vertical, but also effects a spin precession about this axis and thus contributes to the overall spin tune of the machine. By proper choice of rotator parameters, it is possible to keep the spin tune of the machine the same as it were without rotators /4/. This is a convenient feature in operation, especially when turning individual rotator pairs on and off.

The rotators are turned on, of course, by turning on their vertical beam bumps, which are of opposite sign in a pair. Helicity is inverted by inverting both of them. The amplitude of the beam bump is an important design parameter; it must be small to make the rotator technically feasible. In the HERA mini rotator, it is less than 20 cm. A vertical beam displacement of ± 20 m could be accommodated in a 0.5 m high magnet aperture, but this would be unnecessarily elaborate. One can use magnets with normal aperture and move them up and down mechanically. Since there are no quadrupoles within the rotator, the motion is not required to be very accurate, except for keeping the magnets carefully leveled transversely.

The most important property characterizing a rotator, however, is its effect on maximum polarization. In a flat ring, the upper limit for radiative polarization is 92.4 %. The vertical deflection in the rotator decreases this upper limit due to the fact that then, in rotator magnets, the polarization vector does not coincide with the field direction anymore. The effect goes with the inverse square of the rotator length and can thus be reduced by making the magnets weaker and longer. On the other hand, the length of the rotator is restricted by ring geometry and by the absence of focusing within.

A result of J. Buon's survey of rotator parameters /4/ is shown in his "weather map" Fig. 2, where the "isobars" connect rotator samples of equal reduction in maximum polarization. The indicated figure of merit varies between 13 (optimum) and 30 in relative units and refers to the same rotator length. The coordinate axes denote the bending angles in the first two horizontal magnets. The (almost vertical) dash-dotted lines (1), (2), (3) connect rotator samples of equal total bending angle. The dotted curve indicates a singularity in the off-energy correction using the vertical beam bump, which fails to work in that vicinity. The two dashed lines connect samples of vanishing spin tune shift. The square mark is the rotator of the HERA proposal /6/, and the triangular mark is the mini rotator proposed last year /2/, which appears to be a near-optimum solution.

Fig.2: Survey of a two-dimensional variety of mini rotator specimens (J. Buon)

More recently, J. Buon has extended his systematic search to include rotators with non-symmetric vertical bumps, resulting in some further improvement /7/. The outcome is shown in Fig. 3. At a length of 56.6 m and a total horizontal deflection of 20 mrad, it yields a maximum polarization of 82.7 % in the HERA crossing angle geometry pursued at that time. Its off-energy correction by means of the vertical beam bump works adequately in an energy range of ± 3 %, and its contribution to spin tune is practically zero over this whole range. The crossing angle geometry is shown in Fig. 4, and a spin-transparent optic in Fig. 5. The spin matching was done by A. Skuja /8/ and S. Mane /8/ using a program developed by L. Hand /8/. The maximum degree of polarization in this optic, as calculated with the SLIM program developed by A. Chao /8/, was 81 %.

Meanwhile, it was decided to have electrons and protons in HERA interact at zero crossing angle instead of the originally proposed 20 mrad. This decision was based on new results of tracking calculations for crossing beam geometries which indicate a blow-up of the proton beam through the space charge forces of the electron beam already at very low electron currents /9/. The beam-beam forces cause a modulation of betatron frequency and excite synchro-betatron satellite resonances.

This decision posed the problem of how to incorporate the spin rotators in a head-on collision scheme. The principle solution /10/ is shown in Fig. 6 which also indicates, in dashed lines, the former 20 mrad crossing geometry. Essentially, the last rotator bending magnet, with a horizontal deflection of 10.5 mrad, is taken off the rotator in part or even fully /11/ and is transferred into the immediate vicinity of the interaction point, where it provides the required spin rotation as well as a separation of the ≈ 30 GeV electron beam from the (hardly affected) 300-800 GeV proton beam. It is hoped that the fan of synchrotron radiation from this magnet can be passed unobstructed through the detector, since it originates so close to it. The geometry of both beams is symmetric with respect to the interaction point; its details are being worked out in collaboration with detector designers at present.

Reference sheet on HERA rotator design as received March 27, 1984 (Buccia A2)
(Spin rotations in braces) Magnet lengths and strengths idealised for zero coil ends (see table)

design energy 27.5406 GeV
spin time 62.4999

total hor. deflection 20.138 mrad
hor. I.P. displacement 1.479 m

max. Polarisation 82.7% at present best $\frac{1}{g_s}$ -value: $1.62424 \cdot 10^{-3} \text{ m}^{-1}$

Fig. 3: HERA spin rotator, 56.6 m long

Fig. 4: Recent HERA 20 mrad crossing angle collision geometry

Fig. 5: Spin-matched electron ring optic for crossing angle geometry

Fig. 6: New HERA head-on collision geometry with mini rotator

The new geometry, in principle, somewhat deteriorates the spin transparency of the machine in two respects:

- (1) It is not spin-transparent at the position of the transferred "rotator" magnet near the interaction point. Thus, radiation in this magnet will cause some spin diffusion.
- (2) The transferred magnet causes some dispersion in the long straight section such that it is not fully spin-transparent for synchrotron oscillations anymore /12/.

Spin matching for the new optic is being done at present, and in first SLIM runs a polarization of 60 % was obtained /13/. The above effect (1) is not expected to notably reduce polarization, if the transferred magnet is made long and weak enough. The effect (2) is felt more strongly, although being caused by a non-spin-matched dispersion component that only has an amplitude of a few centimetres. It can be cured by introducing in the straight section a beam translation made of two oppositely bending magnets which generate the additional dispersion for restoring spin transparency /20/.

Another possible cure is the method of harmonic synchrotron spin matching that has been proposed to decouple the spin motion from synchrotron oscillations /14,15/. It consists in making the machine spin-transparent for synchrotron oscillations at the nearest integer spin resonance(s) by matching the Chao-Yokoya transparency integrals /16/

$$\int_s^{s+C} \left\{ \begin{matrix} \vec{m} \\ \vec{l} \end{matrix} \right\} (\vec{z} D_x - \vec{x} D_z) k d\sigma$$

to be zero at the resonance(s), where the integrand is periodic and the integral, therefore, does not depend on s. Similarly, harmonic spin matching will also be done for horizontal and for vertical /14/ betatron oscillations.

The design energy of the rotator has so far been 27.5 GeV since this energy can be reached in the HERA electron ring with its initial outfit of rf transmitters and cavities taken from PETRA. However, work with a polarized beam would be greatly eased by going up to 35 GeV where the polarization time, instead of half an hour, will be 10 minutes only and also, as pointed out by J. Buon /18/, the reduction of maximum polarization by the rotator will be smaller. This energy rise will demand the addition of a few superconducting cavity units to the ring, but these will hopefully be available at some time. We were therefore challenged by G.-A. Voss to design a rotator that, by rearranging its components, can be used at 35 GeV as well as at 27.5 GeV. We have since solved this problem in principle, by superimposing a small horizontal beam bump, and are now working out the details of a variable energy mini rotator that works at any energy in the 25 % range between 27 and 35 GeV /19/.

Acknowledgement

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