HIGH ENERGY POLARIZED ELECTRON BEAMS

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Abstract

In nearly all high energy electron storage rings the effect of beam polarization by synchrotron radiation has been measured. The buildup time for polarization in storage rings is of the order of 10^6 to 10^7 revolutions; the spins must remain aligned over this time in order to avoid depolarization. Even extremely small spin deviations per revolution can add up and cause depolarization.

The injection and the acceleration of polarized electrons in linacs is much easier. Although some improvements are still necessary, reliable polarized electron sources with sufficiently high intensity and polarization are available. With the linac-type machines SLC at Stanford and CEBAF in Virginia, experiments with polarized electrons will be possible.

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1. Introduction

In storage rings electrons and positrons are polarized by the so-called Sokolov-Ternov effect (Ref. 1): the spins are aligned antiparallel or parallel to the field lines of the deflecting field by the emission of synchrotron radiation. In the absence of depolarizing effects the maximum achievable degree of vertical polarization $P_{\max}$ is 92.4% and the buildup is described by a simple exponentional law:

$$P(t) = P_{\max}(1 - e^{-t/\tau_p}) \tag{1}$$

The buildup time τ_p is given by

$$\tau_p \text{ [sec]} = 98 \cdot \frac{R^3 \text{ [meters]}}{E^5 \text{ [GeV]}} \cdot \frac{< R >}{R} \tag{2}$$

where R is the bending radius in the magnets and $< R >$ is the average bending radius in the storage ring.

In the presence of depolarizing effects $P_{\max}$ becomes

$$P_{\max} = 92.4 \frac{\tau_p}{\tau_p + \tau_d} \tag{3}$$

and equation (1) becomes

$$P(t) = P_{\max}(1 - e^{-t/\tau}) \tag{4}$$

with

$$1/\tau = 1/\tau_p + 1/\tau_d \tag{5}$$

τ_d is the depolarization time constant.

The depolarization time constant τ_d must be kept large in order to obtain a reasonable net polarization.

Spin and particle motion are linked together by a simple law. When a magnetic field vector deflects an electron by an angle α the spin is rotated around this vector by an angle ψ

$$\psi = \frac{(g-2)}{2}\gamma \tag{6}$$

where g is the g-factor of the electron and γ is the Lorentz factor.

Spin motions and particle motions are therefore different. The particle motion is commutative: the final result is the same even when the same deflections are performed in a different order. The spin motion is described by the rotation of a unity vector, and it is well known that this motion is not commutative. With other words: even when the particle moves on a stable trajectory the spin motion is not necessarily stable. Small spin deviations in one revolution can add up over many revolutions and destroy the polarization.

From the above-mentioned relation between particle motion and spin motion (equation (6)) the energy dependence of the spin motion can be easily derived. For the same deflection angle the spin rotation angle increases linearly with energy. The spin motion is much more violent at higher energies. As a result it is much more difficult to obtain polarized beams at high energies than at low energies.

Another problem arises from the fact that the particle motion is commutative and the spin motion is not commutative. Even when the particle motion can be described in a linear way the spin motion can have nonlinear components.

Considering these statements it becomes evident that in high energy storage rings the nonlinear behavior of the spin motion causes additional depolarizing effects. The appearance of nonlinearities makes it difficult to apply simple programs for simulating the spin motion.

In single and multipass linacs and linear colliders these depolarizing effects do not occur. The only problem to be solved is the construction of a polarized source. Several possible sources are summarized in Section 5.

2. Compensation of Linear Depolarizing Resonances

ACO in Orsay (France) was the first storage ring in which polarization was detected (Ref. 2). A few years later at SPEAR (Ref. 3) a laser polarimeter was installed and the polarization was measured over a wide energy range. Figure 1 shows these measurements. Polarization is obtained over a wide energy range with depolarizing resonances in between. These resonances occur mainly at the following energies:

$$\frac{(g-2)}{2}\gamma = n$$

$$\frac{(g-2)}{2}\gamma = n \pm Q_z$$

$$\frac{(g-2)}{2}\gamma = n \pm Q_x \tag{7}$$

These formulas simply describe resonances at which the spin is kicked by small radial field components revolution by revolution a little bit more into the horizontal direction.

With increasing energy one would expect, according to equation (6), the resonances to become stronger and stronger so that they influence the degree of polarization in between the resonances. A. Chao (Ref. 4) developed a program called SLIM to simulate the effect of beam polarization. This program became a major tool for understanding the polarization effects in high energy storage rings. When this program was applied to PETRA, for example, it was found that closed orbit distortions of the order of 1 mm already reduce the degree of polarization seriously (Ref. 5).

Immediately after PETRA was commissioned, a laser polarimeter was installed to verify these calculations. As was expected, a low level of polarization was found. The assumption was that the polarization was mainly destroyed by so-called integer resonances described in the first line of equation (7). The depolarization mechanism for this kind of depolarization can be described in the following way (Fig. 2). The spin precesses in the bending magnets around the vertical axis and, in the presence of vertical closed orbit distortions, in the quadrupoles around a nonvertical axis, e.g. the radial axis.

If it is assumed that the rotation of the spin in the quadrupoles is mainly around the radial axis, the depolarization mechanism can be simply analyzed. In the bending magnets of Figure 2 the spins are rotated around the vertical axis. This rotation can be described by a matrix. The coordinate system is: z vertical, x radial and y longitudinal.

$$M = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) & 0 \\ -\sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

α is the rotation angle of the spin around the vertical axis in the bending magnet. If it is considered that the spin is rotated in the quadrupoles only around the radial axis this rotation can be described by a similar matrix

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\beta) & \sin(\beta) \\ 0 & -\sin(\beta) & \cos(\beta) \end{pmatrix} \tag{9}$$

where β is the rotation angle around the radial axis.

The basic idea why a particle is depolarized can be simply derived by considering a part of a storage ring consisting of two quadrupoles and a bending magnet in between. When the spin is rotated around the radial axis in the first quadrupole by an angle of β_1, in the bending magnet by α, and in the second quadrupole by β_2, the spin motion in this segment can be described by the spin transfer matrix

$$T = Q_2 \cdot M \cdot Q_1 \tag{10}$$

where the subscripts 1 and 2 stand for the first and the second quadrupoles.

When the matrices in equation (10) are multiplied, the deviation angle of the spin from the vertical β is

$$\cos(\beta) = \cos(\beta_1)\cos(\beta_2) - \cos(\alpha)\sin(\beta_1)\sin(\beta_2) \tag{11}$$

In first approximation this formula can be simplified

$$\beta = \beta_1 + \beta_2 \cos(\alpha) \tag{12}$$

In general the deviation of the spin from the vertical (Δ_{spin}) is of interest. Δ_{spin} is proportional to the square of β. Generalizing formula (12), the total depolarization in the whole storage ring is proportional to

$$\Delta_{\mathrm{spin}} \approx (\sum_{\mathrm{ring}} \beta_i \cos(\alpha_i))^2 \tag{13}$$

Taking further into account that the chosen initial conditions are arbitrary, sine and cosine terms have to be considered

$$\Delta_{\mathrm{spin}} \approx (\sum_{\mathrm{ring}} \beta_i \cos(\alpha_i))^2 + (\sum_{\mathrm{ring}} \beta_i \sin(\alpha_i))^2 \tag{14}$$

This can be interpreted as a Fourier sum. In order to convert equation (14) into a practicable formula, β_i has to be replaced by the field strength in the quadrupole. This can be done by applying a simple relation. In order to rotate the spin by 90 degrees, an integrated field strength of 23 kG·m independent of the energy is required. Therefore the spin deflection angle β and the integrated field strength in a quadrupole are proportional to each other. Rewriting equation (14) leads to the following final result (Ref. 6)

$$\Delta_{\text{spin}} \approx (\sum_{\text{ring}} B_i \cos(\alpha_i))^2 + (\sum_{\text{ring}} B_i \sin(\alpha_i))^2 \tag{15}$$

When this formula is translated into physics the following statement is valid: when the closed orbit has certain Fourier components, the beam will be depolarized. This argument can be inverted: when the beam polarization is small due to closed orbit distortions, a closed orbit can be superposed to the existing closed orbit so that the dangerous Fourier components of the superposed closed orbit compensate the Fourier components of the existing closed orbit. This technique was studied theoretically (Ref. 6) and experimentally (Ref. 7) at PETRA. Figure 3 shows the results of the measurements. Note that the closed orbit changes between 20% to 80% polarization are of the order of 0.1 mm and the total rms closed orbit deviatiation has only changed by an unmeasurable amount.

With this method the first resonance in equation (7) can be compensated. Two different formulations to compensate the rest of them can be found in the literature. Both are theoretical approaches and have never been tested in a machine. The first approach is a general one made by A. Chao: the so-called spin matching conditions (Ref. 8). These conditions can be easily understood by generalizing formula (15) for all sorts of oscillations, e.g. for vertical betatron oscillations. When a photon is emitted the particle performs damped oscillations—betatron and synchrotron oscillations. Taking the vertical betatron oscillations as an example, the depolarization can be explained in the same way as before. The different rotation axes in the quadrupoles cause depolarization. The total depolarization is proportional to

$$\int_0^\infty B_z(s) e^{i\alpha} ds = \int_0^\infty e^{-t/\tau} e^{i\psi_z}(s) e^{i\alpha} \sqrt{\beta_z} k(s) ds \tag{16}$$

$B_z(s)$ are the fields in the quadrupoles, β_z describes the vertical optical behavior of the machine (so-called vertical beta function), τ is the damping time of the oscillation, ψ_z is the phase advance of the betatron motion, $k(s)$ is a measure for the quadrupole strength, and α is the phase advance of the spin motion in the bending magnets defined in a similar way as above.

The infinite integral can be reduced to a finite one by a simple mathematical trick (Ref. 9). With the obvious relations

$$\int_0^\infty ....ds = \int_0^L ....ds + \int_L^\infty ....ds \tag{17}$$

(L is the circumference of the machine) and the periodicity conditions of the betatron and the spin motion

$$\psi_z(s-L) = \psi_z(s) - 2\pi Q_z$$

and

$$\alpha(s-L) = \alpha(s) - 2\pi \frac{(g-2)}{2}\gamma \tag{18}$$

the depolarization is small when the integral

$$\int_s^{s+L} e^{i\psi_z} e^{i\alpha} \sqrt{\beta_z} k(s) ds \tag{19}$$

is zero. This is the first way of formulating a spin matching condition.

The second approach is the following. Equation (19) can also be interpreted as a Fourier integral (Ref. 6). This integral is not zero when one of the following four constants is not zero. This relation can be simply derived by applying the theory of Fourier integrals on equation (19).

$$\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} = \int_s^{s+L} \begin{matrix} \sin(\psi_z) \\ \cos(\psi_z) \end{matrix} \sqrt{\beta_z} k(s) \begin{matrix} \sin(\alpha) \\ \cos(\alpha) \end{matrix} ds \tag{20}$$

In order to minimize the depolarizing effects, these four constants must be minimized by adjusting the optics.

3. The Compensation of Nonlinear Resonances

All arguments up to now can be applied on the simple type of resonances, namely the so-called linear resonances defined in equation (7). For higher resonances the situation becomes more complicated. All calculations up to now are based on the assumption that the rotation of the spin in the quadrupoles is around the vertical axis (see equation (9)). This is no longer the case when the spins deviate significantly from the vertical direction. The particles see both horizontal and vertical field components and the spin is rotated around an axis which has an angle ϕ to the vertical direction:

$$\phi = \arctan(B_x/B_z) \tag{21}$$

With matrix multiplication similar to that done in equation (11), the somewhat lengthy product can be expanded in a series with components proportional to B_xB_z, for instance. The total depolarizing effect is proportional to (Ref. 10)

$$\int_0^{\infty} e^{i\psi_x} e^{i\psi_z} e^{i\alpha} B_x B_z \sqrt{\beta_x}\sqrt{\beta_z} k^2(s) ds \tag{22}$$

leading to resonances of the type

$$\frac{(g-2)}{2}\gamma = n \pm Q_x \pm Q_z \tag{23}$$

This is of course only an example of a depolarizing resonance. All other combinations of Q_x, Q_z, and Q_s (the synchrotron frequency) are possible.

This integral can be treated in a similar way as shown for the linear case (equation (20)). Depolarization only occurs when at least one of the 8 constants is different from zero:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \end{pmatrix} = \int_{s}^{s+L} \begin{matrix} \sin(\psi_z \pm \psi_x) \\ \cos(\psi_z \pm \psi_x) \end{matrix} \sqrt{\beta_z}\sqrt{\beta_x} k^2(s) \begin{matrix} \sin(\alpha) \\ \cos(\alpha) \end{matrix} ds \tag{24}$$

When this theory is extended to a third-order resonance, sixteen spin matching conditions have to be fulfilled. When this formula is generalized, the following statement is valid: in order to compensate a resonance of the nth order, 2^{n+1} matching conditions are necessary. The matching conditions can only be fulfilled by modifying the currents of a quadrupole. Since there is in a storage ring only a limited number of quadrupoles, the possibility of applying such schemes is limited.

4. Nonlinear Resonances and Storage Rings with Spin Rotators

Spin rotators are devices by which the spin is rotated in front of the interaction region into the longitudinal direction and after the interaction region back into the vertical direction. Some of these rotators fulfill the above-mentioned conditions for generating nonlinear resonances: strong deviations of the spin from the vertical and a relatively large vertical beam size. These statements can be explained by studying one of the most elaborate spin rotators, the so-called mini rotator proposed for HERA (Ref. 11). This rotator bends the spin by a combination of horizontal and vertical bendings. As a result of the vertical bending the vertical beam size is increased. T. Limberg *et al.* (Ref. 12) studied the nonlinear behavior of such a spin rotator by using a program taking second-order spin resonances into account: the SITROS program developed by J. Kewisch (Ref. 13). The program observes the decay of the vector sum of the spins when the particles perform betatron and synchrotron oscillations.

In a normal machine without a spin rotator the second-order effects are negligible. With spin rotators the polarization is nearly totally destroyed by the second-order effects. Figure 4 shows the effect. The normally presented curve, polarization vs. energy calculated with the SLIM program, is shown as a dotted line. The polarization is reasonable. When second-order resonances are taken into account and particles with three standard deviations in energy away from the center are observed, the polarization is nearly zero (solid curve). The depolarizing resonances have the form

$$\frac{(g-2)}{2}\gamma = n \pm Q_{x,y} \pm Q_s \tag{25}$$

Taking into account the diffusion speed of particles into the third standard deviation in energy, the depolarization time of the whole beam is smaller by approximately a factor of 10 compared to the polarization time. The net polarization of the whole beam is nearly zero.

In order to compensate this effect in HERA, approximately 25 nonlinear resonances have to be compensated. Since each nonlinear resonance has to be compensated by 8 matching conditions, 200 matching conditions are necessary to improve the polarization.

Although these figures seem to be exaggerated (some of the compensations cover several resonances), it is evident from the calculations that the application of simple linear compensation schemes (Ref. 14) in a machine with vertical deflections is a too-naive approach.

In order to overcome the problem of nonlinear resonances, spin rotators with small excitation of nonlinear resonances have been proposed (Ref. 15,16). The basic idea is to use compensated solenoids. These solenoids rotate the spin and do not (in combination with quadrupoles) produce vertical betatron oscillations and therefore nonlinear resonances. Both systems, a solenoid and a minirotator, are proposed at different institutes (Novosibirsk and DESY) and it will be interesting to see if the experimental results agree with the theoretical predictions.

5. Polarized Beams in Linacs and Linear Colliders

In linacs and linear colliders the depolarizing resonances are negligible. The beam passes only once or only a few times through the same disturbing fields. In storage rings the depolarizing resonances can build up over 10^6 and more revolutions.

Although the problems with depolarization do not exist anymore, a new problem has to be solved: the construction of an efficient polarized source.

One of the best source of polarized electrons or positrons is a storage ring. One could imagine that at the beginning of a linac the particles move in a strong magnetic field emitting photons and becoming polarized. The required field strength for such a source can be easily derived from equation (2). The bending radius is related to the magnetic field and the energy by a well-known formula:

$$R\,[\mathrm{m}] = 33.4\frac{E\,[\mathrm{GeV}]}{H\,[\mathrm{kG}]} \tag{26}$$

With this relation equation (2) becomes

$$\tau_p\,[\mathrm{sec}] = \frac{3.64\cdot 10^6}{H^3\,[\mathrm{kG}]\cdot E^2\,[\mathrm{GeV}]} \tag{27}$$

If it assumed that the deflecting field strength H is, for example, 100 kG (in a superconductive solenoid) the polarization time becomes

$$\tau_p\,[\mathrm{sec}] = \frac{3.64}{E^2\,[\mathrm{GeV}]} \tag{28}$$

From this result it is evident that a fast build of polarization can only obtained at high energies in a storage ring type machine.

For polarization of low-energy electrons different sources have to be used. The most popular source is the so-called GaAs source (Ref. 17). Longitudinally polarized photons emit polarized electrons from the surface of a GaAs crystal covered with a thin layer of Cs. This source has the advantage that the output current can be very high (up to 10^{12}

particles per laserpulse) but the disadvantage that the polarization is limited to $\approx 40\%$. Another advantage is the possibility of reversing the electron polarization in a simple way by reversing the laser helicity.

Sources with higher polarization but lower current use the following effects:

- Stern-Gerlach effect. A neutral alkali beam is emitted from an oven (Ref. 18). The beam enters a sextupole field where atoms with different spins are separated. After the separation the beam is ionized and the polarized electrons are extracted. The polarization of the beam is nearly 85%, but the current is less than 1 μA.
- Optically pumped He-discharge (Ref. 19). A stream of helium atoms passes through a microwave cavity where metastable He atoms are produced. The metastable atoms are optically pumped by a 1.08 μm circularly polarized laser beam and polarized. Afterwards the He-atoms are ionized by collision with a reactant gas and the polarized electrons are extracted. Below 1 μA the degree of polarization is 80%. At higher currents the polarization decreases.

Beside these sources several other sources with a lower output current exist (Ref. 20).

The best source for a given linac must be selected individually for each application. For the polarized version of the SLC, for example, a GaAs source was chosen to be the best (Ref. 21). It produces high currents and therefore a reasonable luminosity.

For fixed target experiments (especially when polarized targets are used) the degree of polarization can be more important than a high current source with low polarization.

For CEBAF, a recirculating linac under construction in Virginia, both a GaAs source and a source with high polarization are under discussion. The technical layout of CEBAF is shown in Figure 5. CEBAF accelerates in a pair of antiparallel superconductive linacs a cw beam of 200 μA up to 4 GeV. After up to four passes through the pair of linacs, the beam is split and sent to three end stations.

With a polarized source several additional spin handling devices have to be installed. The installations depend on the experiments. If, for example, only one end station needs a longitudinally polarized beam, a Wien filter can be installed immediately after the source. This filter rotates the spin in such a way that the spin direction at the entrance is longitudinal. The polarization can be adjusted by a laser polarimeter which can measure both longitudinal and transverse polarization (Ref. 22).

When all end stations need polarized beams at different energies the following way is possible. A Wien filter at the beginning of the interaction region rotates the spin into the vertical direction and in front of each end station the spin is rotated into the longitudinal direction. This is in principle not very simple since all spin handling devices rotate the spin dependent on its energy. As already mentioned a transverse field of 23 kG·m rotates the spin by 90 degrees independent of the particle energy. A spin rotator with simple transverse bending magnets would therefore deflect the beam by different angles depending on the energy of the beam. A device which deflects the beam by the same angle independently of the energy and converts always a transverse spin in a longitudinal direction is shown in Figure 6. The rotator consists of two solenoids and two bending magnets. The free parameter is the relation between the field strengths of the two solenoids. When the energy is changed, the bending magnets have to be adjusted so that the beam leaves the rotator at the same position with the same angle as before and the spin is adjusted by changing the relation of the field strength of the two solenoids. This system works like a high-energy version of the Wien filter.

6. Conclusion

The production of high-energy polarized electron beams is still a challenge for accelerator physicists. It seems (at least at the moment) that experiments with polarized beams (especially longitudinally polarized beams) can be performed much more easily with linacs and linear colliders than with storage rings.

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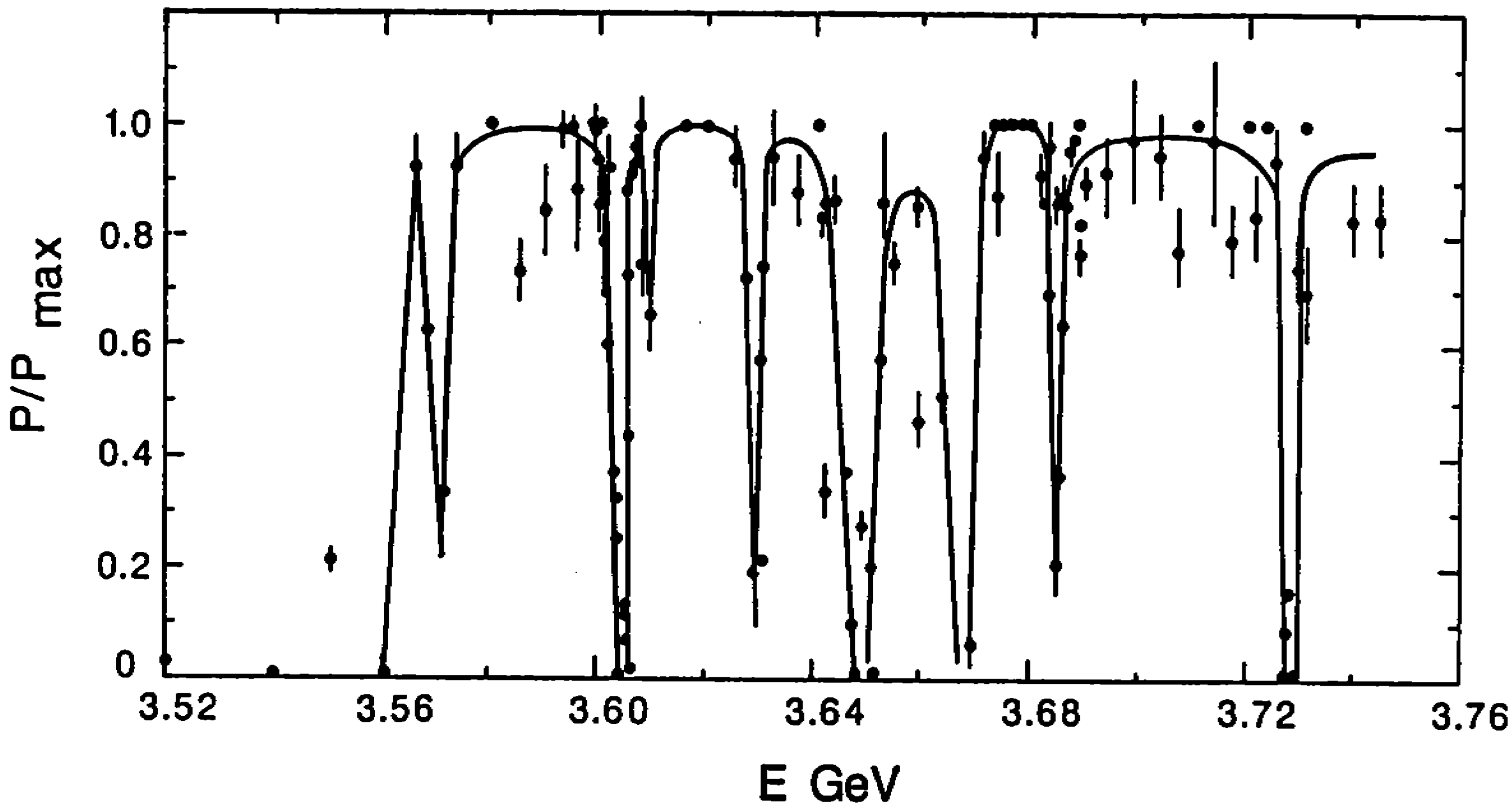


Fig. 1: Polarization vs. energy in SPEAR (Ref. 3).

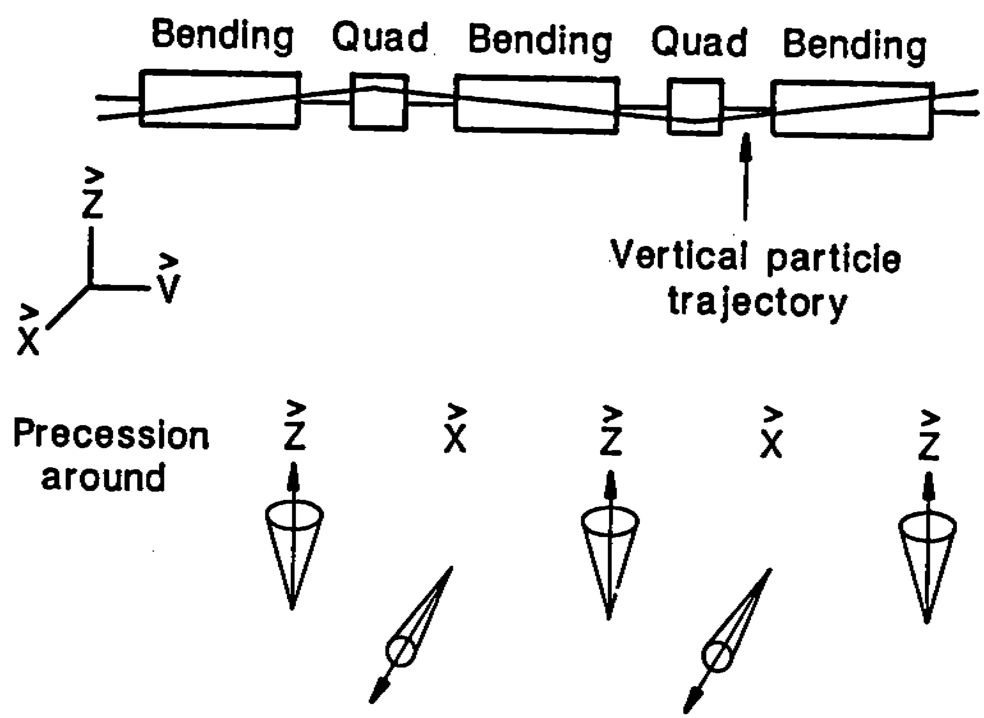


Fig. 2: Schematic presentation of depolarization in a storage ring. The beam is rotated around the vertical axis in the bending magnets and around the horizontal axis in the quads.

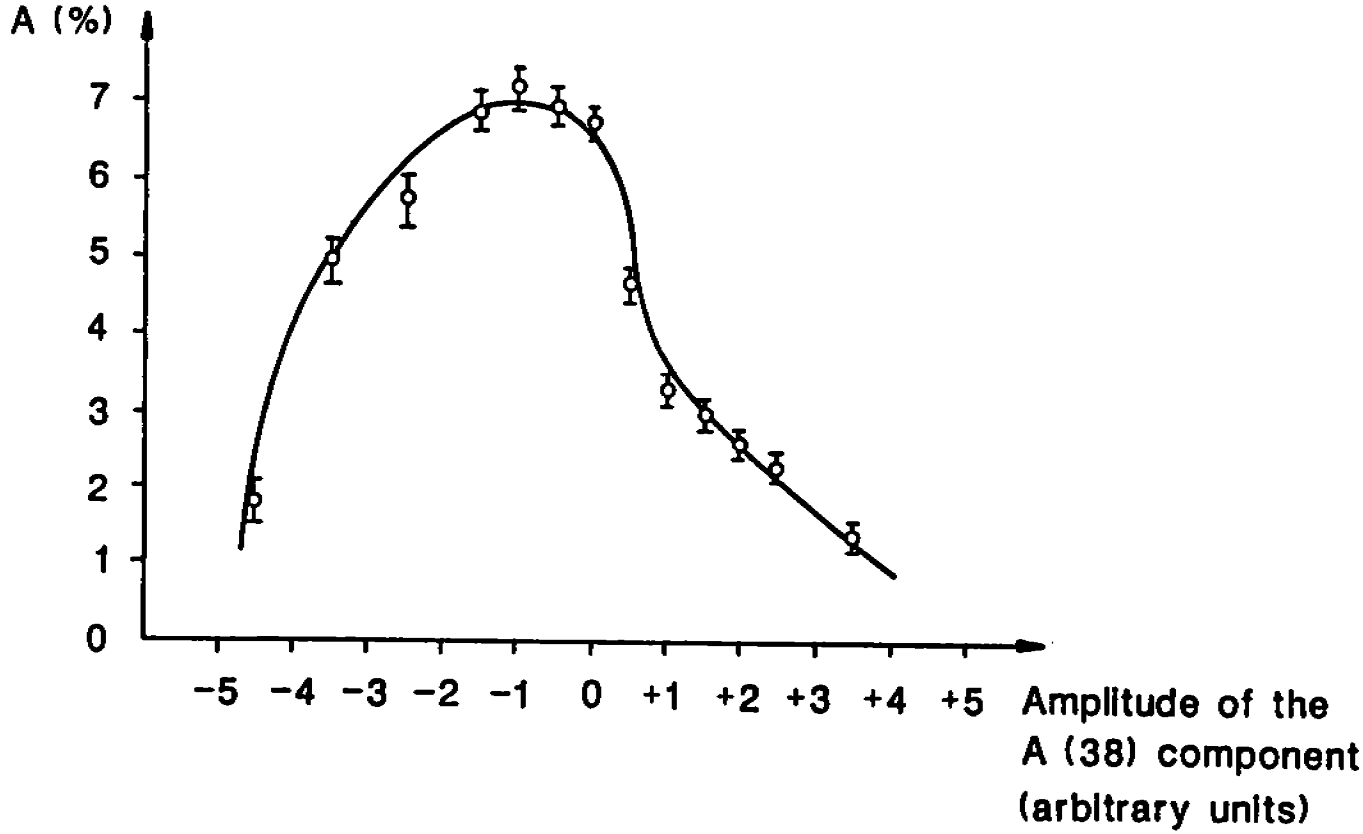


Fig. 3: Experimental results on the compensation of depolarizing effects caused by closed orbit distortions. On the existing closed orbit an orbit is superposed which compensates the depolarizing Fourier components of the previous closed orbit. The asymmetry A is a direct measure for the degree of polarization. On the horizontal axis the linearly increasing amplitude of the superposed orbit is shown.

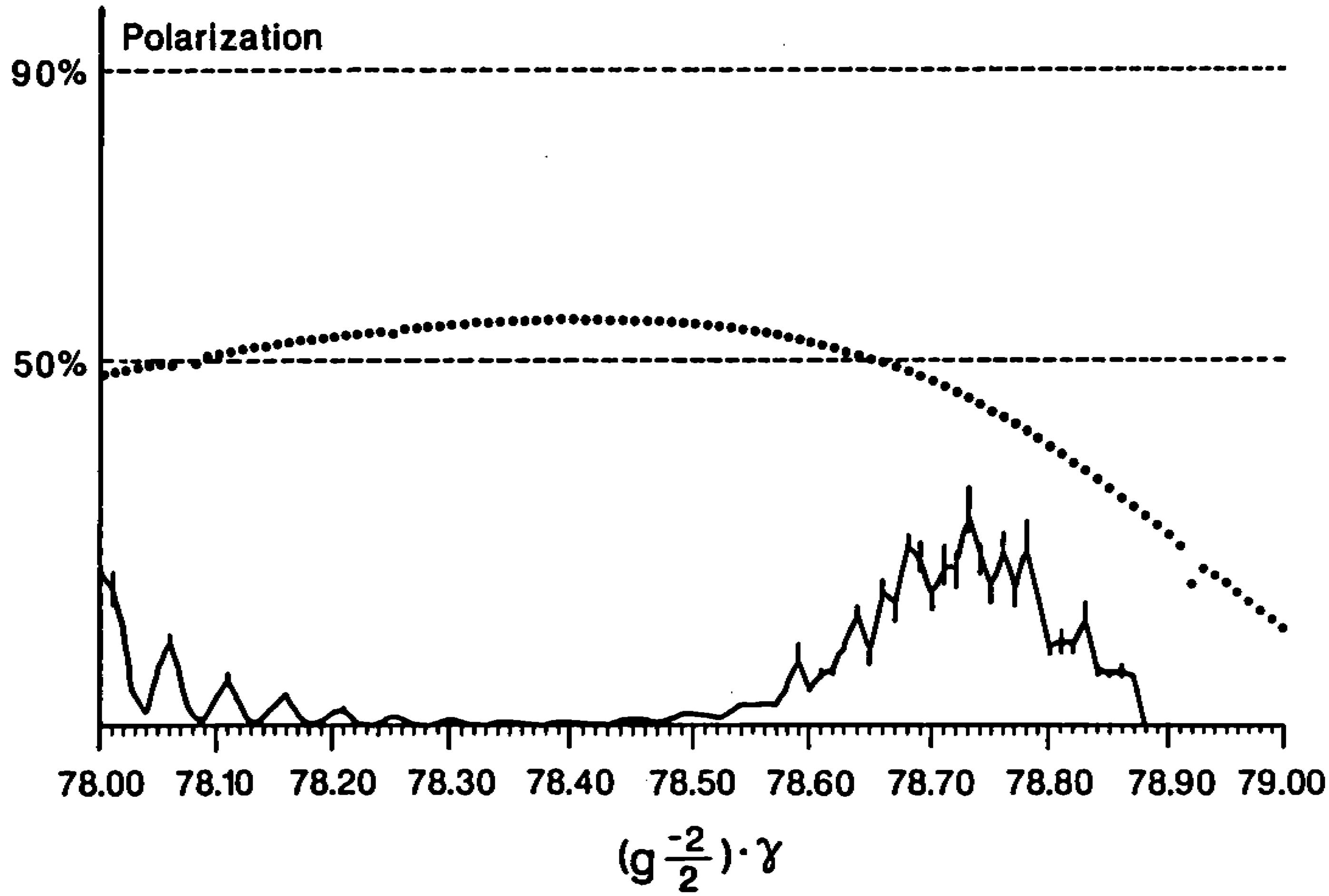


Fig. 4: Depolarization in HERA with spin rotators. The dotted line shows the degree of polarization vs. energy when only linear depolarizing resonances are taken into account. When nonlinear resonances are taken into account and particles three standard deviations away from the central energy are observed, strong depolarizing effects are observed. Multiplying the depolarization effect with the rate at which particles diffuse into the third standard deviation, it can be found that the third standard deviation destroys the polarization of the whole beam completely.

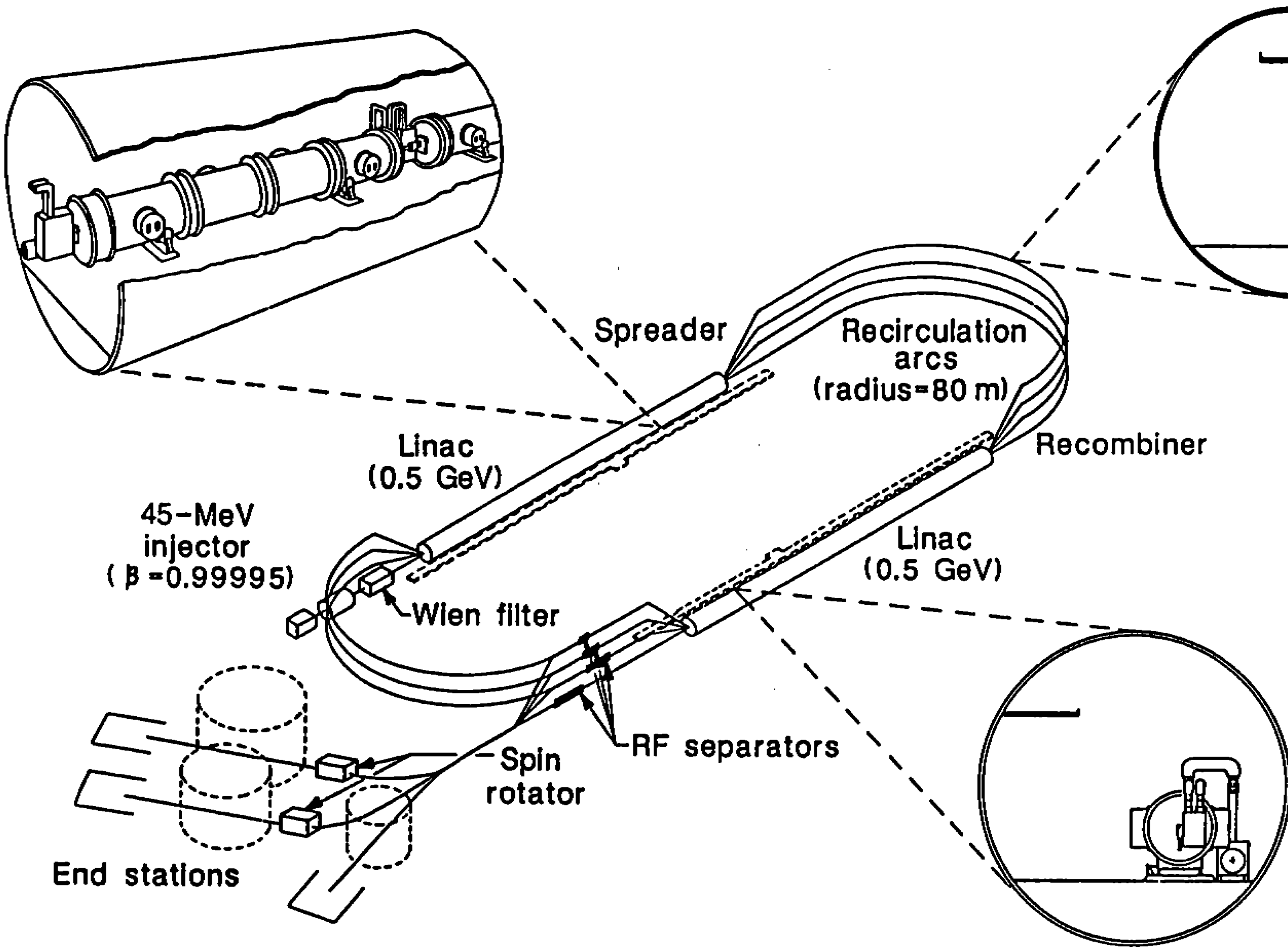
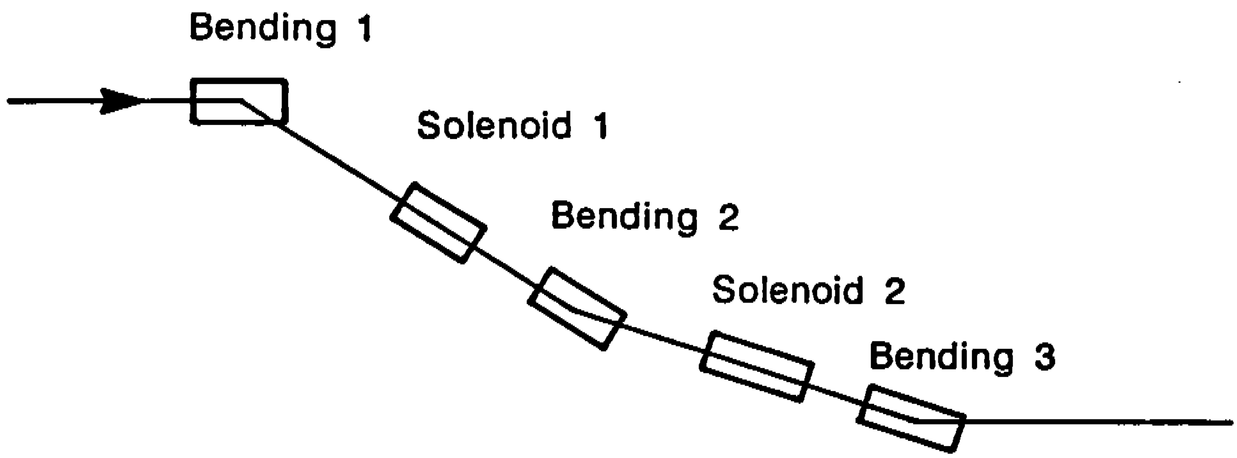


Fig. 5: The schematic layout of CEBAF. The beams are accelerated by two linacs up to a maximum energy of 4 GeV and afterwards directed to three end stations.



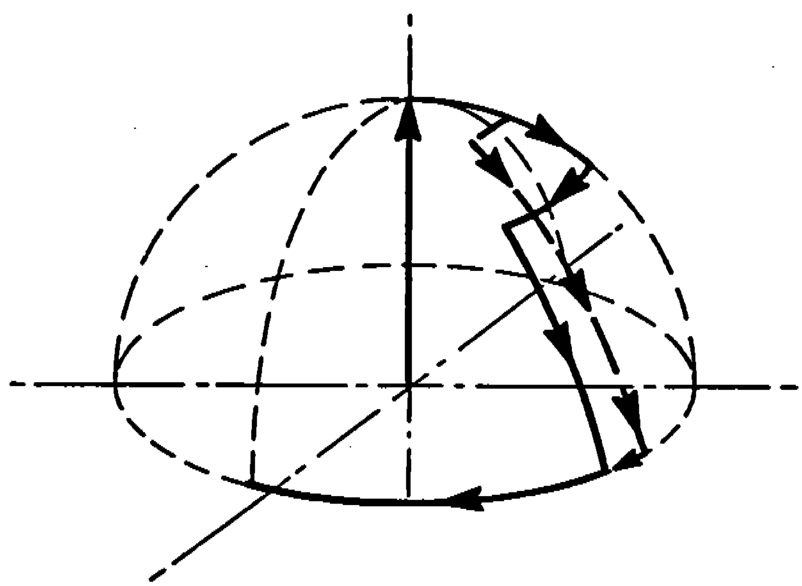


Fig. 6: A possible solution for an energy-independent spin rotator for CEBAF. When the beam energy is changed, the bending magnets are adjusted in such a way that the beam leaves the rotator with the same angle at the same position. The spin is adjusted by changing the strength of the solenoids.

With such a device all three end stations can be provided with longitudinally polarized beams even when the beam energies for the different end stations are different.