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POLARIZED BEAMS IN HIGH ENERGY CIRCULAR ACCELERATORS

In recent years, high energy physicists have become increasingly interested in the possible spin effects at high energies. To study these spin effects, it is desirable to have beams with high energy, high intensity and high polarization. In this talk, we briefly review the present status and the prospects for the near future of high energy polarized beams.

Spin Kinematics - a review

We start with the equation of motion for the spin $\vec{S}$ of a particle in a magnetic field $\vec{B}$:

$$\dot{\vec{S}} = \vec{S} \times \vec{\Omega} \quad (1)$$

The expression for the angular velocity $\vec{\Omega}$ has been derived by Bargmann, Michel and Telegui in 1959:¹

$$\vec{\Omega} = \frac{e}{\gamma m c} \left[(1 + g\gamma) \vec{B}_\perp + (1 + g) \vec{B}_\parallel \right] \quad (2)$$

where $\vec{B}_\perp$ and $\vec{B}_\parallel$ are the components of the magnetic field transverse and parallel to the particle's instantaneous direction of motion and g is a fundamental constant defined to be $(g-2)/2$ with g the gyromagnetic ratio of the particle. For example,

$$g = \begin{cases} 1.793 & \text{for proton} \\ -1.836 & \text{for neutron} \\ .51168 & \text{for electron.} \end{cases} \quad (3)$$

To apply the BMT equation to a circular accelerator, it is convenient to use the coordinate system shown below:

x = radial
 y = vertical
 z = along the design orbit
 θ = angular variable

An ideal particle circulating around the machine along the design orbit experiences only the guiding magnetic field in the $\hat{y}$ direction

$$\vec{B} = B_0 \hat{y} \quad (4)$$

Substituting this into the BMT equation, it follows that, relative to the (x, y, z) coordinate system, the spin $\vec{S}$ now rotates at turns around the $\hat{y}$ -axis as the particle completes one revolution. This quantity, $\Delta\theta$, referred to as the spin tune, is proportional to the energy of the particle. Another conclusion from this exercise is that, since spins of different particles precess around $\hat{y}$ with different phases, the net polarization of the beam, averaged over all particles, must lie in the $\hat{y}$ direction.

In reality, a particle not only experiences the guiding field (4) but may also experience, for example, a perturbing field in the $\hat{x}$ direction, i.e.,

$$\vec{B} = B_0 \hat{y} + B_x \hat{x} \quad (5)$$

In addition to the main precession around $\hat{y}$ with frequency $\Delta\theta$, the spin $\vec{S}$ is also driven by the perturbation B_x , causing it to deviate from the nominal direction $\hat{y}$; and as a result the level of polarization will be reduced. Since B_x is in general small compared with B_0 , this depolarization effect is often weak, but if B_x contains a frequency component which happens to be near the unperturbed precession frequency $\Delta\theta$, a resonant condition is satisfied and strong depolarization may occur.

In a circular accelerator, B_x mainly comes from the vertical excursion y of the particle in the quadrupole magnets. To determine the resonance condition, we need to know the frequency content of y . It turns out that y contains two distinct parts:

$$y = y_{c.o.} + y_p \quad (6)$$

where $y_{c.o.}$ is the closed-orbit part and y_p is the betatron oscillation part. Knowing the frequency contents of $y_{c.o.}$ and y_p , the frequency contents for B_x are found to be

$$B_x \sim \begin{cases} e^{ikP} & \text{from } y_{c.o.} \\ e^{i(P \pm \nu_y)t} & \text{from } y_p \end{cases} \quad (7)$$

where k is any positive or negative integer; P and ν_y are the superperiod and the vertical betatron tune of the machine. The location of depolarization resonances are therefore given by

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up

$$\alpha\gamma = k \quad \text{from } \gamma_{c.o.}$$

(3)

$$\alpha\delta = \nu k \pm \nu, \quad \text{from } \gamma_\theta$$

We can define a resonance width ϵ around each resonance.³ For the closed-orbit resonances, for instance, it is the distance in $\alpha\gamma-k$ from the resonance that the expected polarization is reduced from the ideal value by a factor of $1/\sqrt{2}$. The $\alpha\gamma=k$ resonances are referred to as the imperfection resonances since $\gamma_{c.o.}$ comes from imperfections such as magnet misalignments in the machine. These resonances can be controlled by orbit corrections. The $\alpha\gamma=\nu k \pm \nu$ resonances, on the other hand, comes from betatron emittance of a particle, which can not be controlled in a simple manner. They belong to the family of intrinsic resonances. The width of an imperfection resonance is, roughly speaking, proportional to the k -th Fourier harmonic of the closed orbit. The width of an intrinsic resonance is proportional to the betatron oscillation amplitude of the particle.

One problem that arises is that, since the spin tune depends on energy, it is often necessary to cross resonances during acceleration. The theory of resonance crossing has been studied by Prossart and Stora⁴ in 1966 and later by Orlov and Simonyan⁵ in 1967. A single resonance, whether it is an imperfection or an intrinsic resonance does not matter, of width ϵ is crossed at a constant speed specified by

$$\alpha = \frac{1}{2k} \times \left(\text{the change in } \frac{\alpha\gamma - k}{\alpha\gamma - \nu k \pm \nu} \text{ per revolution} \right) \quad (4)$$

The polarizations of the beam long before and long after the resonance crossing are related by

$$P_{\infty} = P_{-\infty} \left(2 e^{-\frac{\pi}{2} \frac{\epsilon^2}{\alpha}} - 1 \right) \quad (10)$$

It is clear from this P-S equation that, in order to preserve the polarization when crossing a resonance, we have two alternatives. We can either cross with a small ϵ^2/α (weak resonance and fast crossing), or with a large ϵ^2/α (strong resonance and slow crossing). With small ϵ^2/α , the polarization after crossing is essentially the same as before crossing: $P_{\infty} = P_{-\infty}$. With large ϵ^2/α , one expects a nearly complete flip of spin: $P_{\infty} = -P_{-\infty}$.

A series of experiments have been carried out at the Argonne-ZGS^{6,7} to study the resonance crossing effects. It turns out that the resonances for ZGS are relatively weak and the natural way of crossing them is to cross with small ξ^2/α . For imperfection resonances, this is done by minimizing the k-th harmonic of closed orbit through orbit corrections. For intrinsic resonances, the widths ξ can not be easily compensated;⁸ the small value of ξ^2/α is achieved by increasing the crossing speed α . To do that, a pair of quadrupole magnets are activated right before resonance crossing so that V_y is suddenly changed at a high speed. After crossing, the quadrupoles are relaxed and V_y returns to its original value. In a typical proton synchrotron, it is possible to change V_y at a rate about two orders of magnitude faster than we can change α , making this an efficient way of reducing ξ^2/α and thus preserving the polarization.

The situation for ZGS is shown below. The solid lines indicate the locations of the intrinsic resonances. The dotted lines indicate the locations of the imperfection resonances.

ZGS⁹ has successfully accelerated polarized protons from 5v neV/c to 11.75 GeV/c, crossing 10 intrinsic and 21 imperfection resonances on the way. The polarization at injection is 75% and, after crossing an impressive total of 31 resonances, the polarization at 11.75 GeV/c remains about 68% --- a loss of only 7% polarization.

A theoretical estimate for crossing the intrinsic resonances, $\alpha = \nu_x \pm \nu_y$, has been made for ZGS by Ance et al⁴ and is shown in the following table

$Pk \pm$	$P_0(\text{GeV/c})$	$\epsilon \times 10^4$	$\Delta P/P (\%)$ no ν_γ -jump	$\Delta P/P (\%)$ with ν_γ -jump
4-	1.39	1.1	1.9	0.0
4+	2.33	1.2	2.1	0.0
8-	3.65	7.1	61.6	0.9
8+	4.51	7.6	68.6	1.2
12-	5.79	1.6	3.5	0.1
12+	6.63	1.7	3.9	0.1
16-	7.90	9.1	91.0	3.1
16+	8.74	9.5	96.0	3.7
20-	10.01	1.9	5.1	0.2
20+	10.85	1.9	5.3	0.2
24-	12.11	10.7	114.0	6.6
24+	12.94	11.1	116.2	7.4

We see that the resonance widths are in the 10^{-4} to 10^{-3} range. These are not very strong resonances but they are strong enough so that crossing them without ν_γ -jumps would depolarize the beam. With ν_γ -jumps, the loss of polarization is reduced to a comfortable level as is also observed experimentally. The 24th resonances have not yet been crossed at present.

The imperfection resonances at ZGS are typically, about 10 times narrower than the intrinsic ones. Crossing them without orbit correction do not cause serious depolarization. Orbit corrections are nevertheless included in the routine ZGS operation as they do help reducing the depolarization down to a negligible level.

The ZGS technique of using ν_γ -jumps to increase the speed of crossing the intrinsic resonances can be improved and applied to other machines. With some optimization in the distribution of the ν_γ -jump quadrupoles, one may expect

$$\begin{aligned}
 &\text{essentially no loss of polarization if } \epsilon < 0.01 \\
 &\text{some tolerable loss of polarization if } 0.01 < \epsilon < 0.1 \\
 &\text{to need other crossing techniques if } 0.1 < \epsilon.
 \end{aligned}
 \tag{11}$$

The difficulty for $\epsilon > 0.1$ is due to two reasons: (i) the ν_γ -jump can not be made fast enough to assure a small ϵ'/α ; and (ii) even if the crossing speed can be made very fast, the tune ν_γ must jump across the whole width of the resonance which is $\sim 2\epsilon$; the range of the ν_γ -jump therefore has to be > 0.2 , which is difficult since the machine lattice must be stable before, during and after the jump.

One obvious way to cross a wide resonance ≈ 0.1 is to cross slowly, making a spin flip. An experiment has been performed at ZGS on the not-so-wide $af=4-5$ resonance to study this possibility. The next figure compiles their results. The polarization after crossing, is plotted versus the inverse of the crossing speed.

The polarization before crossing is 70%. The solid curve is a Froissart-Stora fit to the fast crossing data points. A free parameter in this fit is the width of the resonance found to be $\xi = 4.6 \times 10^{-4}$. With slow crossing, a polarization of -70% is expected from the F-S theory. The data, however, indicate a value of only -20%. Two reasons for this discrepancy: (i) different particles have different betatron oscillation amplitudes and hence different ξ 's. Particles with small betatron oscillation (hence $\xi \approx 0$) are not spin flipped; and (ii) the spin tune af is modulated by the synchrotron oscillation of the particle. The actual resonance crossing is a complicated combination of the acceleration and the synchrotron oscillation effects.

This experiment shows that fast crossings are preferred whenever possible, but it is perhaps too early to rule out slow crossing with spin flip as a possible alternative for slow syn, very strong, resonances.

Other machines

Calculations of resonance widths for other machines such as AGS, CERN-PS, FNAL main ring and PEP have been done by Ernest Courant.¹⁰ His results for AGS, for example, are shown below:

We notice that, just like ZGS, the intrinsic resonances of AGS are about 18 times stronger than the imperfection ones. The overall resonance strengths for the strong focussing AGS, however, are ~ 10 times stronger than the weak focussing ZGS.

Applying straightforward ZGS techniques of orbit correction and γ -jumps, the present thinking¹¹ is that for AGS with 75% polarization

at injection, it should be possible to accelerate the beam up to 23 GeV/c, crossing 7 intrinsic and 41 imperfection resonances, and keep a 70% polarization. The next resonance at 23.4 GeV/c corresponding to $af=3\sigma+\nu_y$ is rather strong with a width of $\epsilon=0.027$. Crossing it causes a drop of polarization to about 50%. The acceleration will then be stopped at 26 GeV/c in front of the super strong resonance $af=6\sigma-\nu_y$ with $\epsilon=0.10$.

The following table lists the number of intrinsic and imperfection resonances for various accelerators. (Ignore numbers in parentheses for a minute.)

	Machine	Energy (GeV)	# of intrinsic resonances	# of imperfection resonances
	ZGS	12	10 (1)	22 (0)
① {	FNAL Booster	8	1 (0)	14 (0)
	KEK	12	10 (1)	21 (0)
	AGS	30	9 (0)	50 (2)
	CERN-PS	30	12 (0)	55 (2)
	BPS (China)	50	31 (1)	94 (3)
	ISR	11.5 - 31.4	10 (1)	38 (2)
② {	FNAL main ring	8 - 400	250 (10)	749 (30)
	SPS	10 - 400	249 (10)	745 (30)
	Isabelle	29.4 - 400	236 (9)	706 (26)
③ {	PEP	5 - 15	7	23
	LEP	15 - 76	32	124

As mentioned before, ZGS has already succeeded in getting polarized protons at 11.75 GeV/c. Machines grouped under ① in the table are strong focussing machines. It is believed that acceleration of polarized protons in those machines up to near the top energies can be achieved by the ZGS techniques.

Grouped under ② are those multi-hundred GeV machines. The number of resonances for those machines are very large. Although crossing individual resonances may not be a problem, crossing such a large number of resonances still depolarizes the beam.

Electron machines grouped under ③ are listed only for reference since, as will be mentioned later, electrons have a natural way of building up their polarization through synchrotron radiation and it is not necessary to accelerate polarized electrons across resonances.

Deuterons

The question is how to obtain polarized beams of multi-hundred GeV energies. Two alternatives exist: use deuterons in stead of protons¹² or use a "Siberian snake" device.¹³

In the above table, numbers in parentheses are the number of intrinsic and imperfection resonances that have to be crossed if we accelerate polarized deuterons to the top energies of the various machines. These numbers are much smaller than those for protons. The distance between neighboring imperfection resonances is given by

$$\Delta E = \hbar c^2 / a = \begin{array}{ll} 0.5233 \text{ GeV for proton} \\ 13.15 \text{ GeV for deuteron} \\ 0.44065 \text{ GeV for electron} \end{array} \quad (12)$$

The resonances for deuterons are 25 times sparser than those for protons. Using deuterons instead of protons, we should be able to obtain polarized beams at a-few-hundred-GeV level.

There are disadvantages in using deuterons, however. For example, the energy per nucleon is reduced by half. Also, rotation of spin from one orientation to another now requires a magnetic field 25 times stronger than for polarized protons.

Siberian Snake

Another way of accelerating polarized beams to very high energies is to use the ingenious device of a Siberian snake invented by our Siberian colleagues Verbenev and Konuratenko in 1976.¹³

As we mentioned earlier, if the guiding magnetic field seen by an ideal particle is always in the $\hat{y}$ -direction, the spin tune is given by $\nu_{spin} = a\gamma$ and the nominal direction of polarization is $\hat{n} = \hat{y}$. The reason we have to cross resonances during acceleration is that ν_{spin} depends on the beam energy. The idea of a Siberian snake is to somehow obtain an energy-independent spin tune by breaking the condition that the guiding field is always in the $\hat{y}$ -direction.

Consider a conventional circular accelerator whose guiding field is everywhere along $\hat{y}$. Let this accelerator have a mirror symmetry relative to x and z . A "Siberian snake", which rotates the spin around $\hat{z}$ by an angle of π , is then inserted at position 0 . We postpone the detailed design of this device for a minute; for now, it is just a blackbox. The situation is sketched below.

we need to find $\hat{n}$ for the Siberian snake machine. The nominal polarization direction $\hat{n}$ has the property that if an ideal particle starts with a spin in the direction of $\hat{n}$, then the spin comes back to $\hat{n}$ as the particle completes one revolution. Without the snake, $\hat{n} = \hat{y}$ satisfies this property. For a Siberian snake machine, $\hat{n}$ depends on the position. At position A, $\hat{n} = \hat{z}$. Starting at A with $\hat{z}$, the polarization direction $\hat{n}$ precesses around $\hat{y}$ by an angle of $\theta = \pi \alpha$ before it reaches the snake and going through the snake, $\hat{n}$ is reflected to the other side relative to $\hat{z}$ as shown in the figure above. Completing the other half of revolution, the spin returns to $\hat{z}$ at A.

we also need to find $\nu_{sp,n}$ for the snake machine. If we start with a spin not along $\hat{n}$, then by definition, the spin rotates around $\hat{n}$ by an angle of $2\pi\nu_{sp,n}$ as the particle makes one turn. It is straightforward by following the spin motion of a particle for one revolution to see that the spin has rotated by an angle π around $\hat{n}$, corresponding to $\nu_{sp,n} = 1/2$ --- regardless of the energy of the particle.

using a Siberian snake, it is therefore possible to accelerate polarized beams without having to worry about depolarizing resonances. There is, in principle at least, no limit in the highest energy that can be reached with a polarized beam.

Another advantage of a snake machine is that there is a longitudinal polarization at A. This may be quite useful for high energy experiments. we will come again to this point later. Still one more advantage is that the energy spread of the beam does not contribute to a spin tune spread as it does in a conventional machine.

we now go to the actual design of a Siberian snake. The simplest design is to use a solenoid. The spin rotates around the magnetic field which is in the $\hat{z}$ -direction. If one can arrange a snake by using a series of transversely bending magnets, the spin rotates around the transverse axis $\hat{x}$ or $\hat{y}$ in each of the bending magnets, but it is

possible that the net result is a rotation around $\hat{z}$. To decide on which design to use, we make a table:

	proton	deuteron	electron
$B_1 L$ (kG-m)	24.6	1374	46.2
$B_1 L / E_0$ (kG-m/GeV)	37.5	122.3	104.6

in which the magnet strengths needed to rotate the spin by π are listed for proton, deuteron and electron. The transverse strength $B_1 L$ is independent of the beam energy, while the solenoid strength $B_1 L$ is proportional to the beam energy. We see right away that the solenoid design becomes impractical at high energies. (Anything which requires 51140 kG-m is difficult.) (See Appendix.) Deuterons are impractical even using a transverse B_1 design. As we will see later, a B_1 design does not work too well with electrons either, so we are left only with a B_1 design for protons --- but that is indeed good enough.

It is fun to make a B_1 design. What one has to do is to somehow combine a few rotations around $\hat{x}$ and $\hat{y}$ so that the net result is a rotation around $\hat{z}$ by an angle π . One such design, given by Montague,¹⁴ contains 3 bending magnets: one vertical bend of strength $B_1 L = 27.4$ kG-m, followed by a horizontal bend of twice the strength, and then another vertical bend with $B_1 L = -27.4$ kG-m. This works because

$$R_{\hat{z}}(-\frac{\pi}{2}) R_{\hat{y}}(\pi) R_{\hat{x}}(\frac{\pi}{2}) = R_{\hat{z}}(\pi) \quad (13)$$

where $R_{\hat{a}}(\varphi)$ is a rotation of an angle φ around the axis $\hat{a}$.

Radiative Polarization

So far we have not mentioned too much about electrons. Electrons differ from protons and deuterons in that they strongly synchrotron

radiate. It turns out that due to the emission of a synchrotron photon, an electron may flip its spin from an up state to a down state (with a spin flip probability $w_{\downarrow\uparrow}$) or vice versa (with probability $w_{\uparrow\downarrow}$). It was first pointed out by Ternov, Lokutov and Korovina¹⁵ that $w_{\downarrow\uparrow} \neq w_{\uparrow\downarrow}$ and, due to this imbalance of transition probabilities, there is an accumulation of one spin state at the expense of the other state and a natural build-up of "radiative polarization" results.

The polarization builds up in time according to^{16,17,21}

$$P(t) = \frac{8}{5\sqrt{3}} (1 - e^{-t/\tau_p}) \quad (14)$$

where τ_p is the polarization time constant given by

$$\tau_p = 99 \text{ sec} \frac{R \rho^2 \text{ m}^3}{E_0^5 [\text{GeV}^3]} \quad \begin{array}{l} R = \text{mean radius} \\ \rho = \text{bending radius} \end{array} \quad (15)$$

$$\tau_p: \begin{cases} 14 \text{ min} & \text{SPEAR } 3.7 \text{ GeV} \\ 21 \text{ min} & \text{PEP } 15 \text{ GeV} \\ 19 \text{ min} & \text{LEP } 70 \text{ GeV} \end{cases}$$

electrons are polarized along $-\hat{y}$ and positrons along $\hat{y}$. The radiative polarization has been actually observed, like a miracle, at VEPP-2¹⁷ and ACU¹² around 1971 and later at SPEAR¹³ in 1975.

In some sense, we are very fortunate. The equilibrium level of polarization is very high --- 92%! Also the build-up of polarization is along $\hat{y}$ which, presumably due to some deeper reason, coincides with the nominal direction $\hat{n}$ and all the hard work of getting the beam radiative-polarized is not wasted.

As far as polarization is concerned, synchrotron radiation is a good news but it also is a bad news --- it depolarizes.^{17,18} The perturbation resulting from emitting a synchrotron photon excites the horizontal-betatron, the vertical-betatron and the synchrotron motion of the electron with tunes ν_x , ν_y and ν_z respectively. The EM fields sampled by this electron in its subsequent motion thus contains the frequency contents of $k \pm \nu_{x,y,z}$. A resonance occurs if one of the conditions $k \pm \nu_{x,y,z}$ is satisfied.

One may proceed, like the proton case, to define a resonance width ϵ around each of the depolarization resonances. But what makes electrons different is that an electron constantly emits synchrotron photons and if we sum over all the photon emission events, assuming they are uncorrelated, we find that the spin diffuses away from its nominal direction $\hat{n}$. The rate of this diffusion τ_p^{-1} becomes large near a resonance, but it is not always small outside the width ϵ of resonances.

Taking into account both the good news and the bad news of the synchrotron radiation, the radiative polarization builds up according to¹⁷

$$P(t) = P_0 (1 - e^{-t(1+x)/\tau_p}) \quad (14)$$

$$P_0 = \frac{8}{5\sqrt{3}} / (1+x), \quad x = \tau_p / \tau_d$$

which reduces to eq. (14) when $\tau_d \rightarrow \infty$. The equilibrium level of polarization P_0 is lowered from 92% by a factor of $(1+x)$ and the rate of polarization becomes faster by the same factor.

A calculation²⁴ has been made for SPEAR. The results are plotted in the figure above. If we include only the good news, P_0 should be 92%. But if we include also the bad news, P_0 , plotted against the beam energy E_0 , looks rather complicated and contains many hills and valleys. Arrows at the top indicate locations of resonances and hence locations of valleys. Each resonance $a\bar{a}^*k$ is surrounded by 6 sideband resonances $a\bar{a}^*k \pm V_{x,y,z}$. According to this calculation, there should be a good polarization around 3.0 GeV and also around 3.7 GeV.

An experiment was done at SPEAR, using a laser back-scattering polarimeter,²⁵ to measure the beam polarization around 3.0-3.7 GeV. What is plotted here is the polarimeter x vs the beam energy. The solid curve is the calculated result. The agreement with data is reasonable enough.

Similar calculation¹⁶ is also done for PEP. The result is shown below. The expected polarization for PEP is, as we can see, in the 70-80% range in about half the energy space.

wiggler

As mentioned before, synchrotron radiation controls the build-up of beam polarization. One expects then that by controlling, to some extent anyway, the synchrotron radiation, one can control the polarization build-up. Indeed this is the case and the device used are the wiggler magnets. A wiggler is a series of horizontal bending magnets arranged in such a way that the electrons wiggle inside the device but there is very little net effect outside. One such wiggler design may look like this:

it suffers from the fact that $\hat{n}$ is perpendicular to $\hat{y}$ in the rest of the storage ring. As a consequence, the polarization along $\hat{y}$ built up so painstakingly from synchrotron radiation simply does not accumulate. Furthermore, if we inject a beam already longitudinally polarized into the machine, the normal radiative polarization, which tries to build up a polarization along $\hat{y}$ (and destroy any other component of polarization), acts as a depolarizing mechanism. Thus a Siberian snake remains a device mainly for proton machines and not for electron machines.

Beam-Beam Depolarization

Effect of colliding beams on polarization is another problem of concern. In a storage ring, the spin of a particle experiences the highly nonlinear electromagnetic field produced by the electric charges of the on-coming beam. The problem is not that this beam-beam perturbation is terribly strong, but that it is potentially capable of exciting a large number of depolarizing resonances. (If you think the previous results of SPEAR and PEP look complicated, having so many hills and valleys, wait until you see this one.) The locations of resonances in this case are $a\gamma \pm l\gamma_x \pm m\gamma_y = \text{integer}$, where $l = \text{even}$ and $m = \text{odd}$. Given the beam energy, and hence $a\gamma$, there is almost always a depolarizing resonance near by with some l and m .

The beam-beam depolarization problem has been studied by Kondratenko,²⁹ who concluded that the depolarization effect should be tolerable provided that the beam intensity is below the beam-beam stability limit. In other words, the ν_x vs ν_y figure will contain a dense distribution of valleys, but as long as the beam is stable against the beam-beam perturbation, as it must always be the case, one does not have to be very lucky to find hills in between those valleys. The only remaining practical detail is to actually find out where exactly the hills are located, remembering the valleys are densely populated to begin with.

The SPEAR polarimeter group²⁵ has looked at the beam-beam depolarization experimentally. Preliminary results³⁰ show that, in the region around 3.7 GeV, where there is a good single-beam polarization, the polarization persists to exist with colliding beams; while in the region around 3.3 GeV (also with good single-beam polarization), beam-beam collision seems to largely destroy the polarization. It is clear that more work, both theoretical and experimental, still remains to be done.

Summary

It looks reasonably optimistic that high energy polarized beams can be produced in the near future. On the proton front, we have already

the ZGS experiences which are extremely valuable technically, (and perhaps also psychologically) The Froissart-Stora equation, as well as the theoretical calculation of the resonance widths, seem dependable. Extrapolating the ZGS experiences, we expect to be able to obtain 26 GeV/c polarized protons in AGS. Or, if we so choose, we could accelerate polarized deuterons up to near the top energies of Fermilab main ring or Isabella. On top of these, there is the possibility of the Siberian snake which promises, in principle at least, an unlimited highest reachable energy. On the electron front, the radiative polarization has been observed in several storage rings. Calculations taking into account the polarization and depolarization effects of synchrotron radiation seem to work reasonably well. We should have good polarization in roughly half of its energy range of interest.

All problems have not been solved, however. Outstanding among them include: (1) how to produce longitudinally polarized electron beams; (2) studies of beam-beam depolarization in storage rings; and (3) whether a Siberian snake can be applied to an electron machine without seriously reducing the reachable radiative polarization.

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appendix

If we do use a solenoid as a Siberian snake (presumably for a lower energy accelerator), we have to pay attention to the choice of the unperturbed betatron tunes ν_x and ν_y (defined before inserting the snake). The requirement that the lattice must remain stable after inserting the snake restricts their choice. As an illustration, if we let the solenoid length be L and the unperturbed beta-functions at the middle of the solenoid be $\beta_x = 2L/3$ and $\beta_y = L/6$, the shaded area in the following figure indicates the stable region in the (ν_x, ν_y) plane. The figure repeats with period 1 in both ν_x and ν_y . It is calculated for protons.