2
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**WORKSHOP ON POLARIZED PROTON BEAMS
ANN ARBOR, MICHIGAN, OCTOBER 18-27, 1977**

REPORT OF WORKING GROUP ON ACCELERATOR PROBLEMS*

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This workshop has concluded that there are many experimental elementary particle objectives which are uniquely achievable with polarized proton beams. These objectives require both higher beam energies and intensities than are presently available.

The polarized ion source working group has concluded that it looks quite practical to produce polarized H^- sources with output currents of several mA. The significance of this is best demonstrated by the fact that the ZGS operates at its space charge limit using a 6 mA H^- unpolarized ion source and charge exchanger injection. Thus, polarized H^- ions offer the possibility of operating high energy synchrotrons at their "normal" intensity.

With interesting physics to be done and the high probability of adequate intensities for both fixed target and colliding beam machines, the question to be answered is whether or not it is possible to accelerate polarized protons and/or deuterons to energies above the presently available 12 GeV/c of the ZGS and to store beams in a colliding beam machine such as the ISR or ISABELLE. Their questions were considered by the accelerator physics working group whose conclusions are discussed below.

FEASIBILITY OF MAINTAINING POLARIZATION

Polarization of a beam in a circular accelerator tends to be destroyed by the resonances described in the introductory talk at this workshop.¹ The following techniques are possible for coping with this problem:

*Y. Cho, B.W. Montague, W. Kubischta, A. Turrin; E.D. Courant[†] and L. Ratner, Co-Chairmen.

[†]Work performed under the auspices of the U.S. Department of Energy.

1. Referred to as I in this paper.

A) Traverse resonances very rapidly. With pulsed quadrupoles, the tune ν can be changed rapidly and, therefore, the intrinsic resonances

$$\gamma G \pm \nu = kP \quad (1)$$

[See I, eq. (8)] can be traversed fast enough to reduce the depolarization to a small value. This technique has been successfully employed at the ZGS. It also appears feasible for the Brookhaven AGS or CERN PS up to energies around 20 GeV.

However, this method does not apply to imperfection resonances. These are strongest for $\nu = \gamma G$ integral near the solutions of (1). At Argonne, these are overcome by carefully correcting magnet errors near each resonance. To do this, it is necessary to have a good measurement of polarization; thus, the results of the polarimeter workshops are very important here. It would seem possible, again, to make these corrections in the AGS or PS up to energies around 20 GeV.

B) If you can't lick 'em, join 'em. Enhance the resonances by going slowly, obtain spin reversal by the phenomenon of adiabatic passage. But, Argonne experience shows that this may be very difficult at the structure resonances; probably because some particles have small amplitudes, and because synchrotron oscillations can cause particles to traverse the resonance repeatedly in one passage.

C) Use deuterons. The resonances for deuterons are 25 times as far apart in energy as for protons. Thus, the imperfection resonances are now 13 GeV apart rather than 0.52 GeV. Therefore, in the large accelerators (SPS, FNAL main ring, ISABELLE), it may be possible to accelerate polarized deuterons up to energies of around 300 GeV before encountering the most severe structure resonance at $\gamma G = \nu \approx 22$ to 28.

THE SIBERIAN SNAKE - LONGITUDINAL POLARIZATION

Longitudinal Polarization - It may be desirable for some experiments to have the particles polarized longitudinally (helicity states) rather than transverse to the orbit plane. A technique invented by Derbenev, Kondratenko and Skrinsky² (Novosibirsk) makes this possible, and furthermore, avoids all depolarization resonances.

2. Ya S. Derbenev and A.M. Kondratenko, Novosibirsk preprint (1976), Derbenev, et al., submitted to Particle Accelerators (1977).

Consider a ring with two diametrically opposed long straight sections. Suppose in one of these, the beam is longitudinally polarized. In traversing the first semicircular arc, the spin precesses in the horizontal plane, and the angle between spin $\vec{s}$ and velocity $\vec{v}$ increases from zero to:

$$\alpha = \pi\gamma G$$

Now, if in the second straight section the spin can be made to precess through π around the beam axis, the angle between $\vec{s}$ and $\vec{v}$ then changes to $-\alpha$, and in the second semicircle it increases by α back to zero. Thus, the polarization is longitudinal on each traversal of the first straight section.

The precession by π in the second straight section can be accomplished, in principle, in several ways. The easiest to visualize is a solenoid (longitudinal field). In a solenoid, the precession rate is:

$$\frac{d\sigma}{ds} = (1+G) \frac{B\hbar}{B\rho}$$

therefore, the length of the solenoid would have to be such that $B\hbar (1+G) = \pi (B\rho)$ or, for protons, $B\hbar = 1.125 B\rho = 35.2 \text{ Gy kg-meters}$. This is impractical above, at most, a few GeV. However, a similar result can be achieved with transverse fields, taking advantage of the fact that the precession rate in a transverse field is γ times that in a longitudinal field and, therefore, independent of energy. A series of magnets with alternate transverse horizontal and vertical fields can achieve the desired net longitudinal precession. Each of the magnets precesses the spin through an angle of 90° with respect to the velocity and, therefore, must have a field length product of:

$$B\hbar = \frac{\pi}{2} \frac{B\rho}{\gamma G} = 27.5 \text{ kg-m.}$$

The following set of eight such magnets accomplishes the desired precession of π of the spin around the longitudinal axis, and at the same time restores the orbit to its original direction with zero net displacement.

Seven magnets precessing the spin successively through $\pi/2$ around the axes $x, z, -x, -x, -z, x, -z$, followed by a gap of the length of two magnets, and an eighth magnet precessing around $+z$. The first six magnets already accomplish our desired precession, but they also deflect the orbit by an angle $\theta = \pi/2(\gamma G)$ each.

In the vertical direction, the orbit is offset by 2θ by the first 3 magnets and restored by the second three; in the horizontal direction the set of six moves the orbit by a total offset of 3θ . The last two magnets with the gap 2θ between them restore this offset to zero.

With 40 kilogauss, each magnet has to have a length of 0.69 meters, and the whole "wiggler" or "Siberian Snake" has to be 6.9 meters long. This is too long for the existing "small" accelerators such as the AGS or CERN PS, but would fit easily into the SPS, FNAL main ring, or ISABELLE.

The peak vertical excursion in the "snake" is 5.7 cm vertically and 8.5 cm horizontally at 20 GeV, decreasing with $1/\gamma$ for higher energies. Thus, the "snake" seems compatible with reasonable aperture requirement for proton energies above around 20 GeV. (It should be remarked that this scheme is out of the question for deuterons since their γ , at any energy, is 25 times less than for protons, so that a unit magnet would require 685 kG-m.)

An alternative "Siberian Snake" scheme replaces the first six magnets of the snake with three magnets, with $B\ell = 55$ kG-meters each (precession angle π), fields oriented at angles -120° , 0 , and $+120^\circ$ from the horizontal. In this case, the invariant spin in the opposite straight section is radial, rather than longitudinal.

Why is the "Siberian Snake" scheme immune to depolarizing resonances?

In any magnetic field, with or without magnet errors, there exists a closed orbit; along that orbit there exists a periodic spin vector $\vec{s}_0(\theta)$ which repeats on every revolution (its negative $-\vec{s}_0$ also does). The actual spin precesses around $\vec{s}_0(\theta)$.

Now for the "snake" configuration, the frequency of this precession around $\vec{s}_0(\theta)$ is just half the orbit frequency in the absence of field errors. Therefore, if field errors exist, any given field error has equal and opposite effects on the spin on successive revolutions, giving a cancellation. A more sophisticated calculation using the transformation of 2-component spinors by 2×2 SU2 transport matrices, shows that the eigenvectors of the matrix for a whole revolution are insensitive to small perturbations unless the eigenvalues of the SU2 matrix are degenerate, equal to $+1$ or -1 (recall that the precession angle of a spinor is just half that of the corresponding spin). For the "Siberian Snake" the SU2 matrix for the whole revolution is just $i\sigma_2$ or $i\sigma_1$ (depending on which variant is chosen), eigenvalues of which are $\pm i$, as far

from degeneracy as possible. This fact is independent of the precession angle in the arcs and, therefore, of energy; thus, resonances do not arise.

SCENARIOS FOR POLARIZED ACCELERATORS

The following scenarios may be suggested for the production of high energy polarized beams at Brookhaven, CERN or FNAL:

1. Accelerate vertically polarized protons in the source accelerator (AGS, PS, FNAL booster) to around 20 GeV (10 GeV at FNAL), killing the intrinsic resonances by ν -jumps and the imperfection resonances by careful compensation, as is now done at ANL. CPS or AGS 20 GeV beams can be used directly for fixed-target experiments; CPS beam could also be injected into the ISR. If improved sources, described in source workshop, turn out to be possible, intensities and luminosity at ISR may be 10% or more of those now obtained with unpolarized beams.

2. Install a "Siberian Snake" in one of the long straight sections of the SPS, ISABELLE or the FNAL main ring or energy doubler. Transfer the beam from the preaccelerator into the large ring, rotating the spin to the longitudinal direction on the way. Accelerate to top energy in the large ring.

Alternatively, accelerate polarized deuterons in the pre-accelerator, transfer to the large ring and continue to accelerate. Resonances will arise, but can probably be compensated up to the major one at $\gamma G = \nu$, which occurs at about 290 GeV in ISABELLE or the Fermilab accelerator and at 370 GeV at the SPS.

It should be noted, however, that this implies accelerating the deuteron beam in ISABELLE through transition (occurring at 35 GeV). Preliminary estimates indicate that this should not be too difficult, in spite of the slow rate of acceleration, because the acceleration frequency for ISABELLE is very low and, therefore, the longitudinal space charge effect will be relatively weak.

OTHER TOPICS COVERED IN WORKSHOP

Depolarization during storage - It appears plausible that depolarization during storage is governed by the same dynamics as in the case of electron beams, if the damping lifetime of the electron beam is replaced by the growth time of betatron oscillations due to

scattering and/or instabilities.³ If the beam is reasonably far from a resonance, this leads to a polarization lifetime of the same order as the beam lifetime.

Rederivation of Spin Equation - A. Turrin presented a new derivation of the dynamics of depolarization, which shows that the Froissart-Stora result may be modified so as to give complete spin-flip if the time program of passage through resonance is suitably altered.

Possibilities of Further Studies - Argonne Laboratory, with its existing polarized proton accelerator, is in a unique position to undertake experimental studies of storage and acceleration of polarized beams. The working group recommends that Argonne attempt the following:

1. Further study of depolarization, if any, during storage. The ZGS may operate with a flattop of 5 minutes at 6 GeV/c; this should enable them to measure depolarization times with a precision of the order of 10^{-4} sec⁻¹.

2. Further study of adiabatic spin flip. Can the results be improved with a careful control of synchrotron oscillations?

3. A 50 MeV storage machine is being proposed for an investigation of electron cooling of polarized beams. A solenoid here could also be used to verify some aspects of the "Siberian Snake" dynamics (though not its immunity to depolarization during acceleration).

3. B.W. Montague, Report DESY 77/31, May 1977.