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THE FEASIBILITY OF ACCELERATING POLARIZED PROTONS IN THE CERN-PS AND OTHER STRONG FOCUSING MACHINES*

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ABSTRACT

A proposal was made in January, 1975, for a study on the possibility of accelerating polarized protons in the CERN-PS. This is a report of the work performed and the conclusions reached, before the study was wound up. The following problems are discussed: improvements of the source, multi-turn injection into the PS, a collector ring between the preaccelerator and the Linac, depolarizing effects in the PS, and in the transport lines. The conclusions at the end of 1975 were that we should aim for 12 GeV/c as maximum momentum in the first place, but remain hopeful about the possibility of attaining higher PS energies. The results are scaled to other machines to show that polarized protons in, for example, the SPS are unlikely.

INTRODUCTION

After a preliminary investigation[1], a proposal was made[2] in January 1975 for a study on the possibility of accelerating polarized protons in the PS. It was assumed in our proposal, that, with the new Linac now under construction feeding the main PS pulses of ordinary protons for the SPS, the ISR, and the 25 GeV physics experiments, the old Linac would on alternate pulses, feed polarized protons into the PS. Ejection of the beam for fixed target experiments and/or filling of the ISR with polarized protons was envisaged. This study continued throughout the major part of 1975. In October 1975, the Board of Directors of CERN recommended that this work should be wound up in view of the budget cuts and the shortage of man-power to be expected for 1976 and the following years. It was agreed to continue the work on the experimental source and to bring it to completion as planned by the end of 1976. We report here on the original proposal, on the part of the study which was completed, and on the work which is continuing concerning the source. More details can be found in our proposal[2]. Work on polarimeters will be discussed in a separate contribution to this conference[3].

SOURCE

In order to have a useful beam (say 10^{10} protons per pulse 70 to 80% polarized, leading to a p↑-p luminosity of 10^{29} cm^{-2}sec^{-1} in the ISR), we needed a source of polarized protons, with a pulsed current of 100 to 200 μA and a normalised emittance of $E\beta\gamma = 1\ \pi$ mm.mrad, corresponding to 6.8 cm. rad (eV)$^{\frac{1}{2}}$. Present-day polarized ion sources produce continuous beam currents between 2 and 10 μA. Pulsing of the

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dissociator in the source at Argonne resulted in pulsed beam currents of up to 50 μA[4]. This encouraged us to develop in collaboration with H.F. Glavish, Stanford University, an experimental source of at least 100 μA pulsed. ANAC* would provide the essential components, and CERN the peripheral equipment.

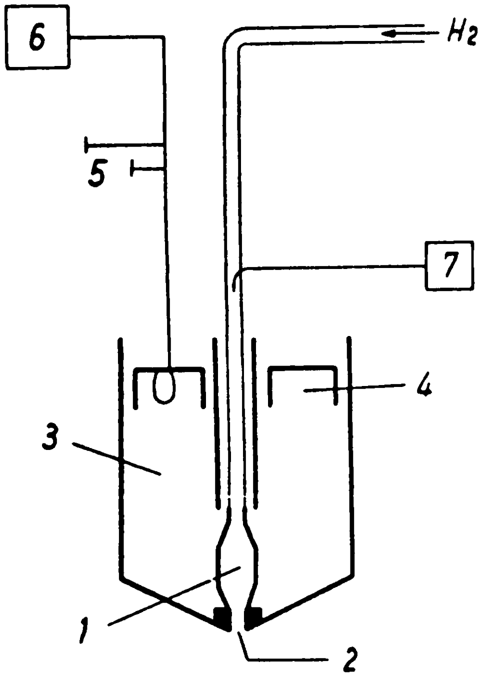

Fig. 1. Microwave dissociator (schematic) 1. Discharge chamber, 2. Nozzle. 3. λ/4 coaxial cavity. 4. Plunger 5 Two-stub tuner. 6. Magnetron. 7. Spark coil for ignition.

The following improvements are planned[5].

- Pulsing the dissociator gas and discharge as at Argonne.
- Improvement of nozzle geometry (elimination of first skimmer, smaller nozzle-sextupole distance).
- Higher sextupole poletips field (about 9 kG), by redesigning the coil geometry.
- Adding a second sextupole ("compressor")[6].
- Increasing the length of the ioniser.
- Provision for pulsing the ioniser.

In parallel, a microwave dissociator has been developed at CERN with the possibility of liquid nitrogen cooling.

At present the components are being assembled and experiments should start early in September. The first measurements with the microwave dissociator (Fig. 1.) showed a dissociation of 50% at ≈ 80 W microwave power input.

STACKING TO INCREASE BEAM INTENSITY

When the source has a sufficiently small radial emittance and/or momentum spread it is possible to increase the intensity by stacking in betatron phase-space (multi-turn injection) and/or in momentum space (collector ring).

a) Multi-turn injection into the PS

Single turn injection intensity in the PS at 50 MeV is $N \lesssim 10^{10}$ particles per mA source current. The normalised acceptance of the PS for multiturning at 50 MeV is ≈ 30π mm mrad. Hence, ideally 30 turns from the polarized source ($E\beta\gamma$ = 1π mm mrad) could be stacked. Since the efficiency decreases rapidly with increasing number of turns, a gain by a factor of 5-10 is more realistic. A source-and-linac pulse of about 100 to 150 μs would be required; this is within the capa-

*ANAC, Auckland Nuclear Accessory Company, Ltd. N.Z.

bility of the old Linac, and would lead to 10^{10} p/p with ≈ 150 μA source current.

b) Collector ring

The collector ring would use the fact that the Linac buckets could be filled from a beam which had $\frac{\Delta p}{p}$ ≈ ± 10 keV spread prior to the buncher, whereas the energy spread of the polarized source is of the order of 100 eV. We consider a strong focusing ring of about $2\pi \times 10$ m circumference which would fill the PS in one turn.

The energy of the preinjector and the field of the ring are "ramped" in such a way that the beam spirals into the collector. At the injection point, the betatron width (W_β) of the beam is decreased and the width due to energy spread (W_s) is enlarged by use of a "low beta, high dispersion optic". Subsequent turns are separated by $W_t = \sqrt{W_s^2 + W_\beta^2}$. The beam is ejected from the collector at a point where the dispersion of the particle orbit is reduced so that W_s is small (Evolution of a proposal by Eaton and Jones (1967[8])).

The number of turns which can be stacked is given by

$$n = (\Delta p/p)_{Linac} \frac{H}{\sqrt{E/\pi + H\,(\delta p/p)^2}} \qquad (1)$$

where $(\Delta p/p)_{Linac}$ is the momentum acceptance of the Linac, H is X_p^2/β_h, X_p is the dispersion function and β_h the betatron function at the injection point. E is the emittance and $\delta p/p$ the momentum spread of the incoming beam. For smooth bending H is invariant, but it can be changed by pathological bending (possible at the low energy of the collector ring). An upper limit to the number of turns which can be stacked in our case is

$$\hat{n} = (\Delta p/p/(\delta p/p) \simeq 100 \qquad (2)$$

In practice we expect numbers of the order of n = 25 since this limit can not be reached because E/π remains the dominating term in equation (1) and $\delta p/p$ is less critical.

ACCELERATION IN THE PS

It is believed that the basic beam observation and beam control equipment would work for intensities down to 10^{10} p/p. Some changes to the RF system would be necessary for intensities below $5\cdot10^{10}$ p/p. It was believed that a method[9] used at the SPS provided a solution.

One of the features of our proposal was to accelerate polarized protons on alternate pulses with the normal ones. For this reason, the facilities for pulse to pulse intensity modulation, designed for different needs, would have been used.

a) Intrinsic depolarizing resonances.

For the PS, the 'intrinsic' resonances[10], occur when

$$\gamma G = 10\,k \pm Q_z,\; k=0,1,2,3\ldots,\; \text{and}\; G = (g-2)/2 = 1\cdot79 \qquad (3)$$

At Argonne, intrinsic resonances are successfully crossed by rapid tune jumps. The same antidote seems possible in the PS. In the proposal[2] we give the parameters of a lens system (with the characteristics of the fast quadrupoles used for the γ-jump at transition energy[11]) to jump the vertical tune in the PS and thus reduce the depolarization per resonance to below 2%.

b) Imperfection resonances.

These resonances, due to orbit distortions occur when $\gamma G = k$, where k=2,3... . The depolarizing effect cannot be reduced by Q-jumping. The solution proposed was a very precise control of the vertical closed orbit. A peculiarity of the PS is helpful in this context. Unlike other machines, for instance the Brookhaven AGS, the PS magnets consist of a focusing and a defocusing half-block which are very precisely aligned and joined. Due to this feature, a parallel magnet displacement, which is more difficult to detect than the tilt, does not, to first order, contribute to the orbit distortions considered here.

Under idealised conditions the polarizations before (P_o) and after (P) crossing a resonance are related by Froissart and Stora's formula[12]

$$\frac{P_o - P}{P_o} = 2\left[1 - \exp(- D/2)\right] \approx D \text{ for } D \ll 1 \qquad (5)$$

Neglecting the effect of straight sections, the depolarization at $\gamma G = k$ is

$$D = \left[\frac{\pi}{\sqrt{G\gamma'}} \, \frac{Z_k}{R} \, k^2(1 + k)\right]^2 \Big/ 2 \qquad (6)$$

Z_k is the amplitude of the k'th harmonic of the deformed closed orbit, and γ' the change of γ per revolution. If we allow a depolarization of $\leq 5\cdot10^{-3}$ per resonance, we have, in the PS (making some simplifying assumptions), a tolerance

$$Z_k \leq \frac{42\cdot5}{k^2(1 + k)} \text{ mm} \qquad (7)$$

A limited number of harmonics can be compensated up to this precision by existing programmable dipoles. Measurement of the beam polarization itself would be the only possibility for judging the effectiveness of the orbit corrections. Measurement has shown that the tilts of the magnets are stable enough over a period of six months and thus a too frequent resetting of the corrections is avoided.

The higher harmonics which cannot be sufficiently reduced by correcting dipoles would be kept small enough by a very careful magnet alignment. In the PS, with 95% probability, all the resonances up to 21 GeV/c could be crossed with $D \leq 0\cdot5\%$ if all the magnets have $|Z_F - Z_D| \leq 0{\cdot}03$ mm, where $Z_F - Z_D$ is the difference in vertical position between left and right magnet edges (tilt). An examination of measurements already made showed that 90% of the magnets had $|Z_F - Z_D| \leq 0{\cdot}1$ mm, so it seems within the realms of possibility that a factor 3 might be gained.

Experiments to investigate the feasibility of adiabatic crossing of the resonances with spin-flip are reported in another paper at this conference[13]. Our conclusions are that spin-flip crossing is complicated by the presence of synchrotron (energy) oscillations and possibly other effects and could therefore only be used to pass some of the resonances in the PS, but probably not too many.

TRANSPORT BETWEEN THE PS AND THE ISR

Lastly we looked at the effect on the vertical polarization (P) of the proton beam from the PS (where it is assumed to be 1) of the transport lines (designated TT1 and TT2) between the PS and ISR[14]. These transport lines are about 500 m in length and include horizontal and vertical bends (due to the difference in height above sea level between the PS and the ISR). The value of the vertical polarization at the entrance to the ISR is given in Figures 2 and 3. At 12 GeV/c it is acceptable for both TT1 and TT2 (≈ 10% depolarization). At higher energies by working at one of the peaks in the TT1 curve. (≈ γ = 23, p ≈ 22 GeV/c), for example, one could have P = 0·91 for TT2, and 0·89 for TT1.

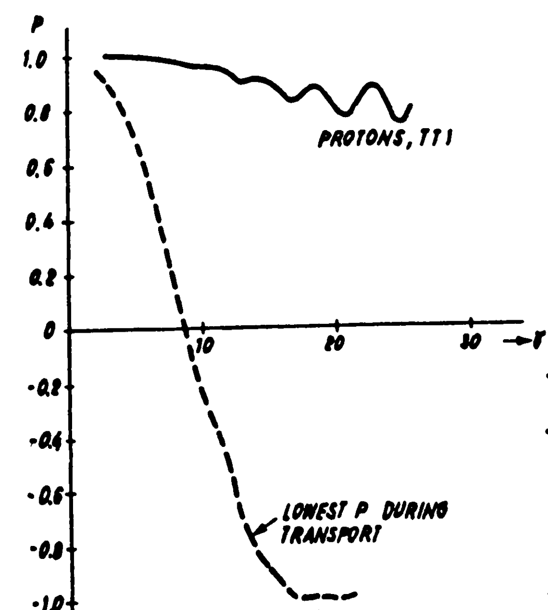

Fig. 2

CHANGE IN POLARIZATION OF CENTRAL IDEAL ORBIT DURING PS-ISR TRANSFER, TT1

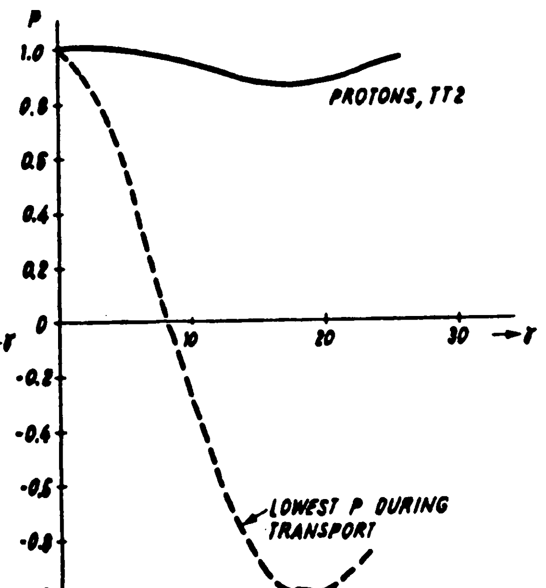

Fig. 3

CHANGE IN POLARIZATION OF CENTRAL IDEAL ORBIT DURING PS-ISR TRANSFER, TT2

APPLICATION TO OTHER MACHINES

To conclude, we scale the results on depolarizing resonances from the ZGS and the PS to the CERN-SPS as a representative example of a 400 GeV machine. Table I gives the number of intrinsic and imperfection resonances.

Table I Number of depolarizing resonances

Machine	ZGS 12 GeV	PS 24 GeV	SPS 400 GeV	SPS deuterons 200 GeV/nucl.
Intrinsic Resonances	12	10	245	10
Imperfection Resonances	21	44	740	30

The strength of these resonances depends on the magnet lattice structure and not all resonances are potentially dangerous. A detailed analysis is beyond the scope of this paper. As regards intrinsic resonances, we shall consider only the resonance $\gamma G = Q_z$ (which does not occur in a weak focusing proton machine, but which is very wide in a strong focusing synchrotron). Table II gives some characteristics of this resonance including a Q-jump system to reduce the depolarization to ≈ 2%. For comparison we include ZGS-parameters concerning the resonance 8 - Q. For the PS and the SPS the D parameter has been calculated from equation (6) taking k = Q and inserting for Z_k the rms beam size

$$\delta_z = \frac{1}{2}\sqrt{\frac{E_v}{\pi\, R/Q}} \qquad (7)$$

where E_v is the vertical emittance.

Table II Parameters relating to the $\gamma G = Q$ ($\gamma G = 8-Q$ in ZGS) intrinsic resonances

Machine	ZGS	PS	SPS
Depolarization parameter D	0.7	2	9
Polarization after resonance (see equation 5) P/P_o	0.4*)	-0.25	-0.99
Q-jump to reduce D to 0.02 Speed $\lvert\dot{Q}\rvert$ (sec^{-1})	10^3	10^4	10^5
Minimum width $\Delta Q = 2\sqrt{(1/\omega_{rev})\lvert dQ/dt\rvert}$ (c.f. [15])	0.02	0.1	1
* T. Khoe et al.[10]			

As to imperfection resonances we neglect the straight sections and in addition approximate the betatron oscillation by a smooth sinusoidal function (smooth approximation). These approximations are rather crude, especially for certain systematic harmonics. Some parameters obtained in this approximation are compiled in Table III. One concludes that polarized proton beams at 400 GeV in the SPS are prac-

Table III Tolerable orbit amplitude and corresponding misalignement to have $D \leq 5\cdot10^{-3}$ (65% confidence level) at imperfection resonances near maximum energy.

Machine	ZGS 12 GeV	PS 24 GeV	SPS 400 GeV
Tolerable amplitude Z_k (mm)	$3\cdot10^{-4}$	$5\cdot10^{-4}$	$7\cdot10^{-6}$
Rms alignment tolerance (mm)	0.25*	0.06**	0.012***

* Rms displacement of the magnet ends (wedge focusing)
** Difference $|Z_F - Z_D|$ in position of left and right magnet edge (tilt)
*** Quadrupole alignment

tically excluded unless one can rely entirely on adiabatic crossing with spin flip. Due to the large number of resonances, high precision of the flip is required. In the PS, compensation of the resonances up to some energy, seems possible due to the peculiarity of the magnet design. By the end of 1975 our conclusions were that, although there was some hope of reaching higher PS energies with a respectable polarization, a physics programme should be based on 12 GeV as maximum energy, until more experience with acceleration of polarized beams had been gained.

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