SOURCES AND ACCELERATORS FOR POLARIZED IONS : A REVIEW

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Abstract : The need for production of polarized particles is emphasized. A review of the different types of sources in use at accelerators is made. New polarization schemes and new uses of polarized sources as targets for storage rings are emphasized.

1. The need for polarized ions sources.

Everybody knows that nuclei are made of nucleons (protons and neutrons) and almost everyone knows that the nucleons have a spin (which in this special case is equal to ½ or half a unit of angular momentum). It means that when plunged into a magnetic field, they are able to rotate or "to spin" around the magnetic field axis.

It is less known that the nuclear interactions are strongly dependent on the orientation of the spins. For example when one proton (or neutron) interacts with a nucleus with spin zero (in fact in which all the nucleon spins are coupled to zero) its interaction is dependent on two terms : a central potential of the order of 50 MeV and a spin orbit potential of the order of 5 MeV. The spin orbit potential is directly responsible for the shell structure of nuclei and hence for their stability.

The basic ingredient for building nuclear interactions is the nucleon-nucleon (NN) interaction between two particles with spin ½. It depends on 5 amplitudes (for the pp or nn case) or 6 amplitudes (for the np case) of which only one is spin independant, all the other ones depending on the relative orientation of the spins. All these amplitudes have about the same strength and if it were not for the tensor NN interaction, the deuteron would not be bound and would not exist in nature.

These features have, since long, called for the use of intense polarized ion sources at low and intermediate energy particle accelerators (electrostatic accelerators, Van de Graaff Tandems, cyclotrons). More recently a new wave of users has come from high energy physics. At very high energy (above a few GeV) strong interactions are supposed to be governed by quantum chromodynamics (QCD) which describe the mutual actions of quarks and gluons. Since helicity (the projection of spin along the momentum of the particle) is conserved in quark-quark and quark-gluon interactions, QCD predicts that, at some high "asymptotic" energy all spin effects must disappear. This prediction is strongly contradicted by experience which shows that there are strong spin effects up to 400 GeV (fig. 1 from ref [1]). This finding has strongly excited a part of the high energy physics community and has pushed for the development of high intensity polarized sources for synchrotrons which has led, in term, to detailed studies of depolarization effects in periodic accelerators.

2. Review of operating polarized sources.

2.1. Introduction.

Progress in polarized sources is extensively discussed at three main types of meetings :
a) International Conferences in Polarization Physics which happen every 5 years, the last one in Osaka in 1985 [2].
b) High Energy Spin Physics Conferences held every 2 years : Serpukhov 1986 [3], Marseille 1984 [4].
c) Topical conferences on polarized sources and targets : Montana 1985 [5], Vancouver 1983 [6].

The reader is encouraged to consult the proceedings of these various meetings for more details on the subject.

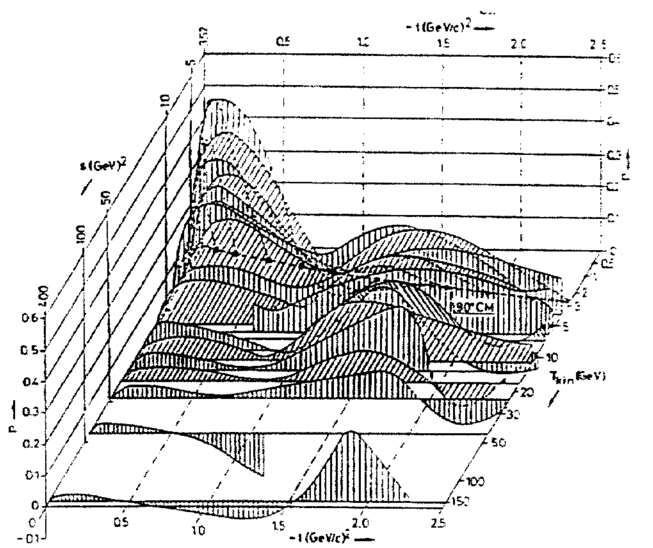

Figure 1. The s- and t-dependence of polarization in pp elastic scattering. The curves $P = f(t)$ at fixed s are hand-drawn fits to data at representative energies. The curve $s_{min} = f(t)$ represents the energy above which the corresponding t-value is accessible. At this curve, $\theta(CM) = 90°$ and $P = 0$ for identical particle scattering.

Fig. 1

Most polarized sources produce protons (spin ½) and less frequently deuterons (spin 1). Polarized heavy ions (^3He, ^6Li, ^7Li, ^{23}Na) have also been accelerated recently [7]. The principles for production of polarized particles are the same for the diverse kinds of particles and I will mainly describe polarized proton sources, adding only complements when needed.

There are essentially three types of sources : the atomic beam source, the Lamb-shift source and the most recent optical pumping source. Most sources can produce positive or negative polarized ions, depending on the ionization scheme but Lamb-shift sources are most suitable for negative ions production.

2.2 Atomic beam sources.

2.2.1. General principles. Eleven atomic beam sources were reported at the last Montana meeting [5] and altogether there must be more than 20 sources working in the world. Atomic sources are the most intense for DC operation and they are still highly competitive for pulsed operation.

A schematic diagram of an atomic beam source is schown in fig. 2. The atoms are produced by dissociation of hydrogen or deuterium gas in a RF discharge which takes place in a vessel ended by a nozzle. A skimmer usually limits the dimension of the atomic jet. The atoms enter a 6-pole magnet in which they are submitted to a restoring force $F_r = -kr$ by the inhomogeneous magnetic field. The atoms with electron spin projection $m_J = +½$ are focussed while the atoms with $m_J = -½$ are repelled from the axis, recombined on the pole pieces and finally pumped out. After having passed in the sextupole magnet the atoms are electron-polarized but their nuclear polarization is still zero since one-half of the protons selected is in state $m_I = +½$ and the other half in spin state $m_I = -½$. They pass then in a set of radio-frequency transitions which select states producing non-zero nuclear polarization.

For spin - ½ particles the polarization is defined as :

$$P = (n^+ - n^-) / (n^+ + n^-)$$

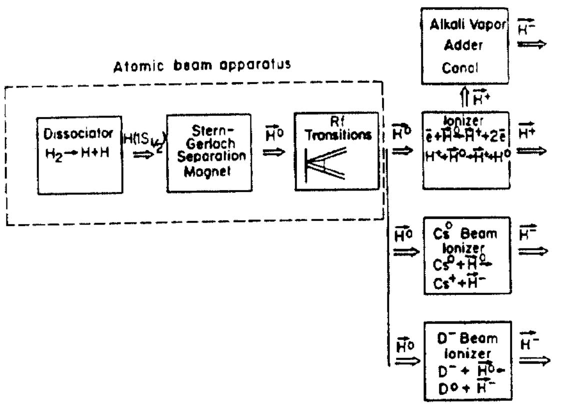

Fig. 2 Schematic diagram of the atomic beam sources with different ionizer schemes.

where n^+ and n^- are particles in nuclear spin state $m_I = \pm \frac{1}{2}$ respectively. Deuterons having a spin 1 can take three different orientations $m_I = +1$, 0 and -1 when submitted to a magnetic field and one can define 2 quantities : a polarization

$$P = (n^+ - n^-) / (n^+ + n^0 + n^-)$$

and an alignement

$$A = (n^+ + n^- - 2n^0) / (n^+ + n^0 + n^-)$$

Physicists like to work in an irreducible tensor representation in which transformations under rotations are much easier to handle and they define, following the Madison Convention [8], a vector polarization t_{10} and a tensor polarization t_{20} such that :

$$t_{10} = \sqrt{\frac{3}{2}}\, P \qquad t_{20} = \sqrt{\frac{1}{2}}\, A$$

The next step is to ionize the H^0 or D^0 atoms to produce positive ions by electron bombardment. This is usually done inside a magnetic field given by a solenoïd which produces a confinement of the electrons and increases their interaction length with the atoms.

Efficiencies of these devices are of the order of 3 to 5 %. Polarized ion beam intensities of 500 μA have been reached [9].

Atomic beam sources are also used to produce negative ions by charge-exchange as shown in fig. 2.

2.2.2/ Improved atomic sources. Improvements on atomic sources are under way with the goal of obtaining intensities of a few mA.

a) Pulsation. When the operation mode of the accelerator permits it (e. g. in a synchrotron) an improvement of a factor 2 can be readily obtained by pulsing the gas flow and the R. F. power in the dissociator. This improves vacuum conditions and allows higher R. F. peak power resulting in a better dissociation efficiency. The Saturne polarized source is pulsed down to 900 μs for an injection time in Mimas of 800 μs.

b) Dissociator cooling. By lowering the temperature of the atomic beam one may expect to gain on two levels ; 1) the solid angle of the sextupole magnet can be increased as T^{-1} and 2) the beam density should increase as v^{-1} or $T^{-\frac{1}{2}}$. Altogether improvements should go as $T^{\frac{3}{2}}$ and at the Ann Arbor Conference in 1981 there were predictions that by going from room temperature to LHe a gain of 590 would be obtained. Many attempts have been done since to lower the temperature of the atomic beam and one distinguishes now warm (room temperature) sources which are almost extinct, cold sources (cooled by LN_2 down to 77°K or by LHe down to 4°K) and ultracold sources which aim at temperatures of 1°K or less (still under development).

It has been realized that there are effects off-setting some of the gains 1) the gas density in the dissociator is limited by gas scattering, 2) recombination on the walls of the dissociator increases, 3) the divergence angle at the exit of the sextupole increases resulting in a lower ionization efficiency.

Altogether the gains have scaled like $T^{-\frac{1}{2}}$ where T is the temperature of the atomic beam which is higher than the temperature of the cooling device. For example a beam temperature of T = 34°K (v = 750 m.s^{-1}) has been measured at ETH for a nozzle cooling of 20°K [10]. The use of an accomodator, separated from the dissociator, which cools the beam without cooling the discharge results in a much scharper distribution as seen on fig. 3 obtained at ETH.

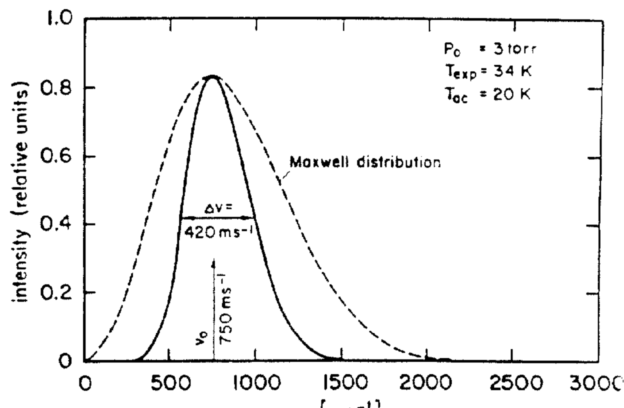

Fig. 3

c) Sextupole matching. What is important is that as many atoms as possible enter the ionization volume and one way to do it is to use 2 short sextupoles instead of a long one, the first one accomplishing the separation between hyperfine states and the second one acting as "compressor" to focalize atoms of different velocities into the ionizer as shown in fig. 4 [11].

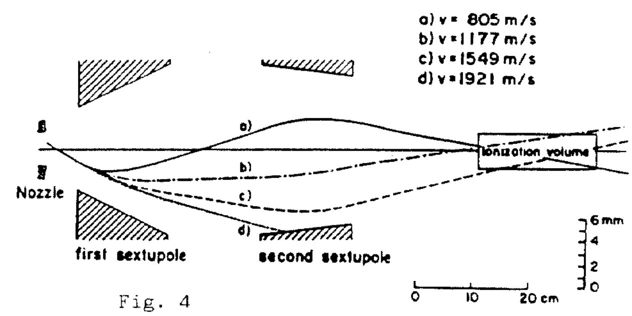

Fig. 4

d) Ionizer. The electron bombardment (EB) ionizer seems to have reached its optimum design. For D. C. sources, electron cyclotron resonance (ECR) ionizers are investigated [12]. Their high electronic density makes them a good choice for an ionizer. Moreover since the plasma in an ECR source is neutralthere are no space charge-effects on the ion beam and the resulting energy spread is very small (typically <5 eV) compared to some keV in an EB ionizer. One problem is the possibility of depolarization through spin-flip of the atomic electrons. Calculations [13]show that for a low-power ECR (50 W) at 2,45 GHz which is best suited for ionization of singly charged atoms, significant depolarization is unlikely. Tests carried out at Karlsruhe and SIN have resulted in production of up to 150 μA of 85 % tensor polarized deuterons in 60 mm.mrad. MeV$^{\frac{1}{2}}$, a gain of a factor 2 to 5 compared to an EB ionizer [14]. The best ionizer so far has been developped at INR Moscow by the colliding beam method [15] using the charge-exchange reaction $\vec{H}^0 + D^+ \rightarrow \vec{H}^+ + D^0$. Intensities up to 6 mA of polarized proton beam with polarization 76 % have been obtained

[16] . Unfortunately this ionizer works only with short 100 μs pulses at 1 Hz which makes it not suitable for D. C. operation or even for most synchrotrons.

2.2.3. Ultra cold atomic sources. It has been observed that atomic hydrogen can be stabilized against molecular recombination by polarizing the electron spins and densities as high as 10^{17} at cm^{-3} have been achieved [17] at very low temperatures (<1° K) : in this situation atomic collisions occur only in triplet state which is repulsive, then prohibiting recombination. An interesting application is the possibility of making a very intense ultra-cold (T=0.3°K) source (fig. 5).

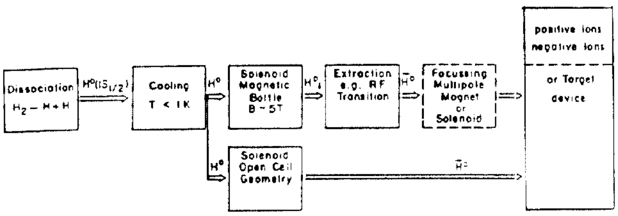

Fig. 5

The thermal energy of atoms at 0.3°K is much smaller than their magnetic potential energy in a field of a few Teslas as shown in fig. 6. Then the

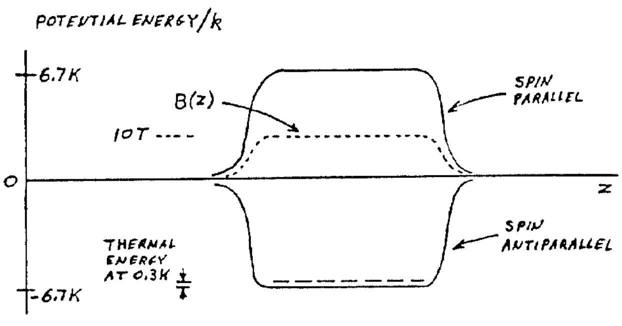

Fig. 6 Schematic representation of the "magnetic bottle".

atoms with electron spin $m_J = + \frac{1}{2}$ are completely repelled at the entrance of a solenoïd with B > 5 T whereas atoms with electron spins $m_J = - \frac{1}{2}$ are pulled into the solenoïd and then stored.

The natural polarization is given by

$$P = \exp (- 2\mu_o B/kT) - 1$$

where μ_o is the Bohr magnetॆon and k the Boltzmann constant. At T = 0.3°K and B = 10 T the electron polarization is 100 %.

Ultra cold sources are investigated at CERN [18] and by a Michigan-MIT-Brookhaven collaboration [19].

2.3. Lamb-shift sources.

About 15 Lamb-shift sources are operational. For a long time they have reigned at accelerators producing negative ions like Van de Graaff tandems or the TRIUMF cyclotron. They are now challenged by atomic beam sources which produce higher intensities but with larger emittances and, more recently, by optical pumping sources.

The schematic diagram of a Lamb-shift source is shown in fig. 7. One starts from an intense beam of positive ions produced by an R. F. source, a duoplasmatron or an ECR source, resulting in a beam having a very small energy spread (20 eV) and low emittance. The H^+ or D^+ ions, accelerated to 500 eV per nucleon, are neutralized in a Cs charge exchange cell where a substantial fraction is converted to $^2S_{1/2}$ atoms. The undesired spin states are induced to decay to the $^1S_{1/2}$ ground state by small electric fields. The remaining ^2S atoms are then ionized selectively by charge-exchange in currents up to 1-3 μA with 80 % polariza-

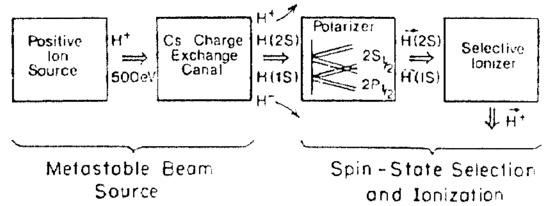

Fig. 7 Schematic showing the basic components of a Lamb-shift polarized ion source.

tion can be obtained but recent progress has been slow: the brightness of the H^+ beam seems to be limited and quenching of metastable atoms by Cs^+ arise in strong space-charge.

2.4. Optically pumped sources.

With the advent of high power lasers the use of optical pumping to produce polarized alkali vapour has become very effective [20] and there were 3 operating optically pumped sources discussed at the Montana workshop at the end of 1985 : INR (Moscow) [21] , KEK (Japon) [22] and TRIUMF (Vancouver) [23].

A schematic diagram is shown in fig. 8. Electron

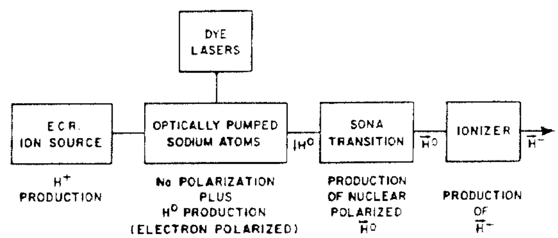

Fig. 8

polarized sodium atoms exchange their polarized electrons with a 5 kV high intensity beam of positive ions resulting in electron polarized hydrogen atoms. Spin exchange occurs in a strong magnetic field (> 10 kG)in order to prevent depolarization. The hydrogen atoms are then nuclear polarized in a Sona-type transition. Positive ions are obtained by a further charge-exchange in a Ne cell or negative ions are produced by attaching one more electron from an unpolarized alkali vapour.

The unpolarized hydrogen source may be a duoplasmatron (INR Moscow) or an ECR source working at 16.5 GHz (KEK) or at 28 GHz (TRIUMF). The polarizing medium is sodium pumped by a combination of broadband and single frequency laser at λ = 5896 A°. With a pumped laser power of 1 $W.cm^{-2}$ about 10^{18} spin-polarized atoms can be produced per pulse leading to currents ranging from 10 to 250 μA of H^- and up to 4 mA of H^+ with polarizations of the order of 40 % to 65 % and very small emittance as shown in table 1. The pulse width is 30 μs at 1 Hz (Moscow) to 150 μs at 20 Hz (KEK) giving macro duty-cycles of 3 x 10^{-5} to 3 x 10^{-3} which make this scheme less interesting for D. C. machines or even synchrotrons with slow injection.

Despite these shortcomings polarized sources based on optical pumping are certain to overcome the reign of Lamb-shift sources for production of negative ions and they may be a strong competition for pulsed positive atomic beam sources. They may be well suited for producing also tensor polarized deuterons [24].

2.5. Conclusions on polarized sources.

The goal for reaching the space-charge limit with polarized sources, proclaimed since the very first Polarization Symposium in Basel, in 1960, is now under reach at many accelerators (e. g. at Saturne we are now accelerating 2 x 10^{11} polarized deuterons per cycle in Mimas for a limit of 6 x 10^{11}). There is no doubt that with sources based on powerful new schemes (ultra-cold, optical pumping) producing many mA of polarized particles this goal will be achieved soon.

TABLE 1

Laboratory	Particle	I (μA)	Polarization	Emittance Normalized
INR Moscow (pulsed)	H^+	4 000	65 %	1 mm.mrad
	H^+	250		
KEK Japan (pulsed)	H^-	60	58 %	0.01mm.mrad
		150	40 %	
TRIUMF Vancouver D. C.	H^-	10	50 %	0.02mm.mrad

3. Accelerators for polarized sources.

With the increase of interest for polarized beam experiments there is not a single type of ion accelerator which does not produce polarized beams. Japan, for example, has equipped 2 Tandems, 2 cyclotrons and one synchrotron with polarized sources.

Positive ion sources are used at :
- low energy electrostatic accelerators (INR Moscow),
- most cyclotrons (Eindhoven, Tokyo, Osaka, SIN, Karlsruhe, Texas A and M, Berkeley, Birmingham),
- Synchrotrons (Saturne).

Negative ion sources are used at :
- Tandem accelerators (TUNL, Erlangen, Munich, Giessen, Cologne, Tsukuba, Kyushu , Zurich, U. of Washington, Madison),
- cyclotrons with H^- injection (TRIUMF),
- linac (LAMPF),
- synchrotrons with H^- injection (Brookhaven, KEK).

This list is not exhaustive.

Most Van de Graaf tandems are able to accelerate polarized particles. Since these are electrostatic machines there are no depolarizing resonances to cross and the direction of the polarization is conserved from the source to the high energy end of the machine, and, with some precaution, to the target. Polarization components in all three directions (x, y, z) are then easy to obtain directly at the source where power requirements are minimal.

Cyclotrons are also equipped with polarized sources and in most cases there is no problem with depolarizing resonances except for the Manitoba Cyclotron which had to be restricted for the acceleration of polarized deuterons, the protons being fully depolarized. Acceleration of polarized particles has been made more efficient with the development of axial injections (Grenoble, Karlsruhe, Groningen, SIN injector). Polarized intensities of a few μA can be obtained.

Amongst larger machines all 3 meson factories (TRIUMF, SIN, LAMPF) have a strong program in polarization. TRIUMF accelerates H^- up to 515 MeV and they have decided to switch from a Lamb-shift source to an optical pumping source which is well advanced [23] and aims at obtaining 50 μA of H^- before the end of 1988.

LAMPF accelerates $\vec{H}^-$ at the same time as H^+, with a Lamb-shift source of moderate intensity and they have also decided to switch to an optical pumping source.

SIN is a special case since the injector is able to accelerate polarized protons up to 72 MeV but primary polarized protons are not usually accelerated in the Ring Cyclotron. Polarized experiments (essentially for the Nucleon-Nucleon program) were done with protons polarized up to 40 % by small angle scattering, this mode of operation being compatible with the production of secondary beams (μ, π, n). But acceleration of highly polarized primary protons up to 580 MeV has been made when the intensity was needed.

Amongst synchrotrons, Saturne is the only machine accelerating polarized protons (up to 3 GeV) and polarized deuterons (up to 2.3 GeV) and it holds the world record for intensity (2×10^{11} ppp with Mimas). The source Hyperion is of the cold atomic beam type [25]. Proton polarization ranges from 90 % at 500 MeV to 80 % at maximum energy. Deuteron pure vector polarization of 60 % can be obtained and tensor polarization is ∿ 85 % (combined with a vector polarization of 30 %). There are no depolarizing resonances for deuterons. The use of polarized particles represent 60 % of the machine time.

KEK (12 GeV) accelerates polarized protons up to 3.5 GeV, intensity $3 - 9 \times 10^8$ ppp and polarization 30 – 40 % with an optical pumping source [22]producing 60 μA with a polarization, at the source, of 55 ± 5 %. Acceleration up to 5 GeV is being studied [26].

Next in energy is the Dubna synchrophasotron which uses a cold atomic beam source (Polaris) to accelerate 5×10^8 polarized deuterons up to 10 GeV [27].

The AGS at Brookhaven is equipped with a cold atomic source producing 25 μA of H^- with a pulse width of 300 μs. The intensity reaches 2×10^{10} ppp at 22 GeV/c, the highest energy for a direct polarized beam with a polarization near 50 %. A new source which has produced up to 60 μA of H^- by collisional charge exchange with D^- is being installed [28].

Besides high energy electron machines for which the production of polarized beams is a completely different problem since the electrons are naturally polarized by synchrotron radiation, one must signal that the acceleration of polarized protons in the future 20 TeV on 20 TeV SSC is seriously debatted [29], a task which would require a careful study of depolarizing resonances and the use of numerous "Siberian snakes" to preserve the polarization as shown in fig. 9.

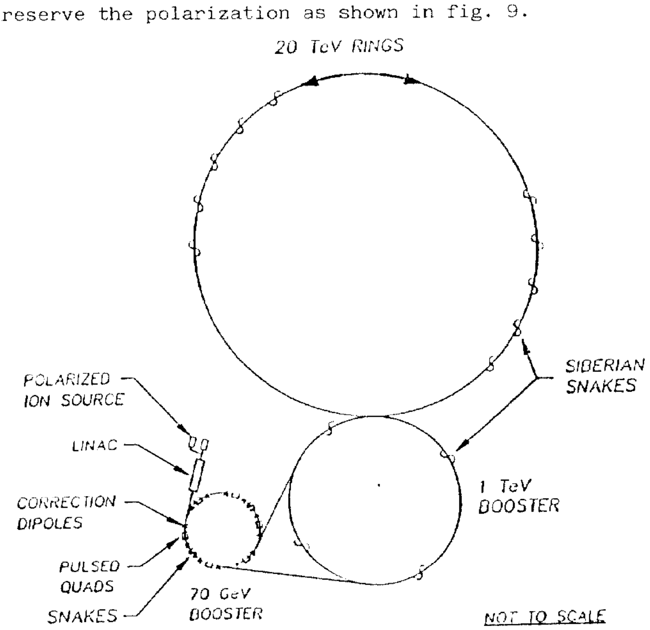

Fig. 9 : Polarized protons at SSC

Finally it must be stressed that polarized sources can also be used as polarized targets either as jets crossing circulating beams but also as storage cells. With the advent of storage rings (LEAR, IUCF, CELSIUS, COSY, HERA) these applications will become more and more important.

References

[1] F. Lehar et al in ref 3, vol. 2, p. 122.

[2] Proc. 6th Int. Symp. Polar. Phenomena in Nucl. Physics, Osaka, 1985. J. Phys. Soc. Japan 55

(1986) suppl.

[3] Proc. 7th Symp. on High Energy Physics, Protvino,1986.

[4] Proc. 6th Int. Symp. on High Energy Physics, Marseille, 1984. Journal de Physique, Colloque C2, 46 (1985) suppl, ed J. Soffer.

[5] Proc. Int. Workshop on Sources and Targets, Montana (1986), Helvetica Physica Acta 59(1986) Helvetica Physica Acta 59 (1986) pp 513-806, ed. S. Jaccard and S. Mango.

[6] Proc. Polarized Proton Ion Sources, Vancouver (1983), AIP Conf. Proc. 117 (1983), ed G. Roy and P. Schnor.

[7] H. Jänsch et al, Nucl. Inst. Meth. A254 (1987) 7 G. S. Masson et al, Nucl. Inst. Meth. A242 (1986) 196.

[8] Madison Convention : Proc. 3 rd Inst. Symp. Polar. Phenomena in Nucl. Reactions, Madison, 1970, ed H. H. Barshall and W. Haeberli.

[9] P. A. Schmelzbach et al, Nucl. Inst. Meth. A251 (1986) 407.

[10] W. Gruebler in ref. 2, p. 435.

[11] W. Z. Zhang et al, Nucl. Inst. Meth. A260 (1987) 313.

[12] R. Geller et al, Nucl. Inst. Meth 175 (1980) 281 and contribution to this conference.

[13] T. B. Clegg et al, Nucl. Inst. Meth. A238 (1985) 195.

[14] L. Friedrich, E. Huttel and P. A. Schmelzbach, Preprint (June 1988), P. A. Schmelzbach, private communication.

[15] W. Haeberli, Nucl. Inst. Meth. 62 (1968) 355.

[16] A. S. Belov et al, Nucl. Inst. Meth. A255 (1987) 442.

[17] R. W. Cline, J. T. Greytak and D. Kleppner. Phys. Rev. Lett. 47 (1981) 1195.

[18] T. O. Niinikoski et al, in ref. 6, p. 139.

[19] D. Kleppner in ref. 4, p. 665.

[20] L. W. Anderson, Nucl. Inst. Meth. 167 (1979) 363.

[21] A. N. Zelenskii et al, Nucl. Inst. Meth. A245 (1986) 223.

[22] H. Sato et al, preprint KEK 87-124, nov. 1987, submitted to Nucl. Inst. Meth. A.

[23] W. M. Law et al, preprint TRI-PP-87-66, Aug.87

[24] M. B. Schneider and T. B. Clegg, Nucl. Inst. Meth. A254 (1987) 630.

[25] J. Arvieux, AIP Conf. Proc. 80 (1982) 185.

[26] H. Sato, preprint KEK 87-147, Jan 1988, submitted to Japanese Journal of Applied Physics.

[27] A. A. Belushkina et al, in ref. 3, p. 215.

[28] A. Herscovitch, A. Knopov and T. O. Niinikovski, Rev. Sci. Instr. (april 1987).

[29] A. D. Krisch, in ref. 2, p. 31.