A Review of Polarized Ion Sources for Cyclotrons

P.W. SCHMOR
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., V6T 2A3

Abstract

Polarized nuclei have become an important nuclear physics probe. Present day experiments are often precision experiments measuring rare processes. These experiments require that the polarized ion source provide beams with high polarization, high beam current, exceptional beam quality and long term reliability. The three types of polarized ion sources in use on cyclotrons are; a) the Lamb Shift source, b) the Atomic Beam (ground state) source and c) the Optically Pumped source. Each type can provide intense beams of nuclearly polarized light ions which are either positively or negatively charged. Heavy ion polarized ion sources for cyclotrons are being developed. The ideal choice for a particular cyclotron depends on the precise experimental requirements. This review article presents a brief description of each of these sources, outlining the current capabilities and the future prospects.

1. INTRODUCTION

Although polarized ion sources have been in use for more than 30 years, their performance continues to improve to meet the changing demands of current experiments. Present day experiments are often precision experiments measuring rare processes and require intense, stable beams within a small emittance. For example, the measurement of the parity violation amplitude in *pp* scattering at TRIUMF requires a modest polarized current of only 0.5 μA at 230 MeV but with a challenging spin-flip coherent current modulation less than 1 part in 10^5 at a spin flip rate of approximately 100 Hz. Another experiment examining pion production in *np* scattering used cyclotron slits to reduce, substantially, the cyclotron emittance and even though the experiment required only 0.5 μA at 475 MeV, it was necessary for the ion source to provide more than 8 μA of polarized H^-.

There are a number of factors which must be taken into account in deciding the best polarized source for an accelerator. The experimental programme defines parameters such as current, polarization, spatial polarization uniformity, stability requirements, spin-flip criteria and polarized species. The accelerator defines the allowed beam emittance, the overall source size and the required ion charge state. The administration is concerned with the cost and risk. The risk is often minimized by purchasing an ion source from a commercial company in order to minimize the research and development required to meet the experimental requirements.

Polarized ions are generally produced in an ion source comprised of three distinct stages. The three components are shown schematically in figure 1. The first step is to produce an intense high quality atomic beam. Next this atomic beam is electronically polarized in a magnetic field by selecting the hyperfine states of one of the Zeeman levels. Nuclear polarization is achieved by inducing transitions from selected remaining hyperfine states (of an undesired nuclear spin direction) to the unoccupied hyperfine states (of correct nuclear spin). Finally the remaining beam which is now nuclearly polarized is ionized in the presence of a magnetic field to preserve the polarization. The strength of the magnetic field depends on the particular hyperfine states being ionized.

Fig. 1. A schematic representation of the three distinct processes involved in making a polarized ion beam.

2. LAMB-SHIFT POLARIZED ION SOURCE

A comprehensive review of Lamb-shift sources, published six years ago, is still valid.[1] The basic techniques used in the Lamb-Shift source (LSPIS) to obtain a polarized beam are shown schematically in figure 2. Protons at an energy of about 550 eV (or ^{2}H, ^{3}H, ^{3}He at the same velocity) are directed through a cesium vapour target where a large fraction of the ions are neutralized. Many of the atoms in the beam emerging from the cesium target are in the metastable 2S states. Unwanted hyperfine states are quenched to the ground states within the magnetic field of a solenoid either by a static electric field (which removes, from the four metastable hyperfine states, the two states with similar electron spin orientation) or by an rf field (spin filter) which allows only one of the four metastable hyperfine states to transit the region of the rf field without quenching. If two of the hyperfine states are used it is necessary to follow the solenoid by a Sona type transition to transform from the two states with similar electron polarization to two states with similar nuclear polarization.[2] Selective ionization of the metastable atoms occurs in a magnetic field (to preserve the spin direction). The polarized atoms in are selectively (compared to the unpolarized atoms in the ground states) ionized either to positive ions in an iodine vapour or to negative ions in an argon vapour.

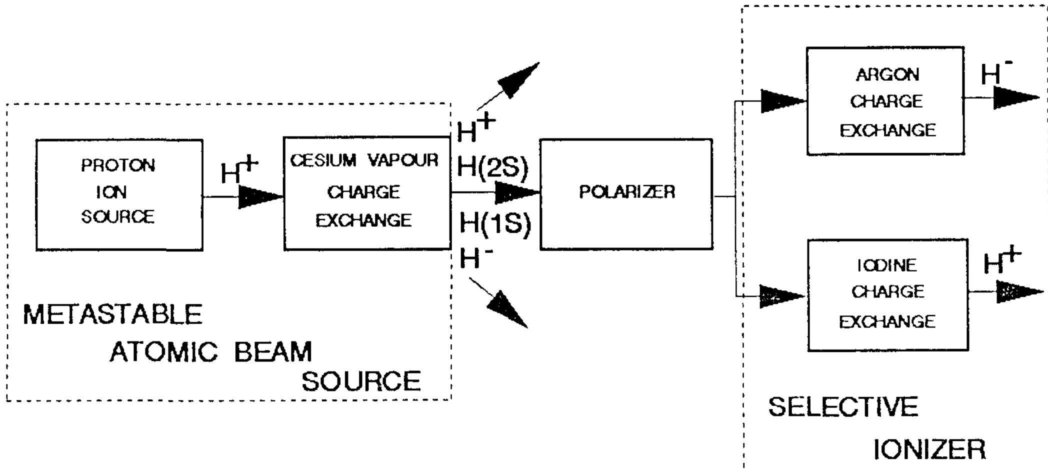

Fig. 2. A schematic of a Lamb-shift type polarized ion source. Two ionizing options are shown.

Frequently the selectivity of ions originating from metastable atoms (over those from atoms in the unpolarized ground states) is enhanced with the use of an emittance defining aperture.

The current from a LSPIS is limited to about 1 μA per hyperfine state by space charge forces. The beam leaving the cesium charge exchange target contains un-neutralized ions. These ions give rise to an electric field which quenches and limits the flux of metastable atoms.[3] The polarization depends somewhat on the current but is generally in the range of 0.8 to 0.85. The LSPIS is an economical and reliable choice for a cyclotron with its relatively small acceptance. However the restriction in maximum current limits the source's usefulness for many of the present-day precise experiments.

3. *ATOMIC BEAM POLARIZED SOURCES*

Figure 3 depicts schematically the elements of an atomic beam ion source (ABIS). H (or ^{2}H) atoms are generated in a dissociator by a radio-frequency discharge and then formed into a low velocity atomic beam with the aid of a cooled nozzle and a system of skimmers. Tapered sextupole magnets are used to separate (Stern-Gerlach technique) one set of hyperfine states (with the electron spin aligned to the magnetic field) from the other set (with the electron spin aligned in the opposite direction). Hyperfine transitions, to convert the separated atomic states which now have a similar electron spin direction (electron polarization) to states of similar nuclear polarization, are induced by

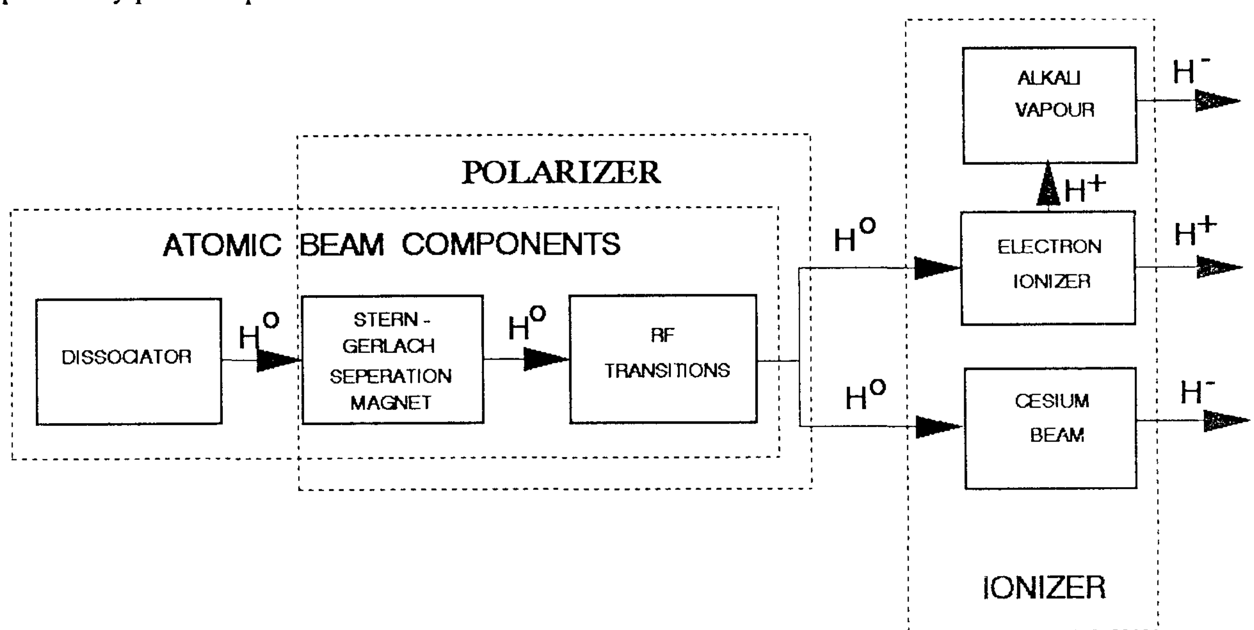

Fig. 3. Schematic of an Atomic Beam Polarized Ion Source showing several ionizing options.

applying the appropriate radio-frequency field. The interested reader can find more detailed descriptions in the literature.[4]

There are a number of approaches being used to ionize the nuclearly-polarized, neutral, atomic beam. To produce positively charged ions, an electron impact ionizer is used. This is achieved either by producing an intense electron beam with a hot filament in a solenoid magnet or by using the electrons generated in an electron-cyclotron-resonance (ECR) heated plasma. Space charge forces within the intense electron beam give rise to an energy spread in the polarized ions which limits the amount of polarized beam which can be matched into a cyclotron. The ECR ionizer avoids the space charge problems of the intense electron beam by using the electrons in a quasi neutral plasma and the resulting polarized beam is considerably brighter (more current within a given emittance). However, experience has shown that the polarization is slightly degraded ($\sim$5%) by the ECR ionizer. The PSI source, for example, produces about 150 μA of positive beam with about 79% polarization within a normalized emittance of less than 1.2π mm-mrad. The ETH group has reported positive currents as high as 400 μA.[5] To produce negatively charged ions, the positively charged ions are accelerated to about 5 keV prior to being directed through an alkali vapour target where about 7% of the positive ions are converted to negative ions by double charge exchange. An alternate approach to producing the negative ion beam has been to use charge exchange directly between the slow moving polarized, neutral atomic beam and a counter-flowing, coaxial, neutral beam of cesium atoms at 40 keV. This approach provides a highly polarized beam (>95%) of excellent emittance ($\sim$0.35 π mm-mrad normalized by $\beta\gamma$). At the INR in Moscow, very high currents ($\sim$6 mA) have been achieved (albeit with 30 μS long pulses at a 1 Hz repetition rate within a normalized emittance of 2π) by making use of the larger charge exchange cross-sections of $^2H^+$ (compared to electrons) in a plasma to ionize directly the polarized atoms.[6] A similar arrangement to the INR scheme with the exception that the source be designed to make use of charge exchange with $^2H^-$ (instead of $^2H^+$) has been proposed for producing negatively charged hydrogen ions.

4. OPTICALLY PUMPED SOURCES

A review of the status of optically pumped polarized ion sources in 1990 has been given by York.[7] The current status of the TRIUMF source can be found elsewhere in these proceedings.[8] The optically pumped polarized ion source (OPPIS) is based on a proposal by Anderson.[9] A schematic of an OPPIS using charge exchange is shown in figure 4. Lasers are used to achieve electronic spin alignment in an alkali vapour. Initially, as proposed by Anderson, sodium was pumped with dye lasers tuned to the D1 transition at 596 nm, but more recently titanium sapphire lasers are being used to pump rubidium (or potassium) vapour at 795 (770) nm. Protons are directed at an energy of about 2 to 5 keV through the polarized vapour where by charge exchange they can pick up a spin aligned electron. The charge exchange process must take place in a large magnetic field ($\sim$ 2.5 T) in order to preserve the spin alignment. After removing any un-neutralized particles by means of transverse electric fields , the beam emerging from the alkali vapour is a neutral atomic hydrogen beam with two hyperfine states (of similar electronic spin) predominately occupied. A Sona type transition is then used, as in the Lamb-shift source to transform the electron alignment to a nuclear alignment prior to ionization. The nuclearly polarized atomic beam is ionized in either an alkali to form negative ions or in helium to form positive ions.

The OPPIS has limitations on the output brightness (current\emittance^2) as a result of the large magnetic field required to preserve (decouple L & S) the electron polarization during charge transfer. It has been proposed to avoid this problem by using spin exchange with a neutral hydrogen beam instead of charge exchange with a proton beam.

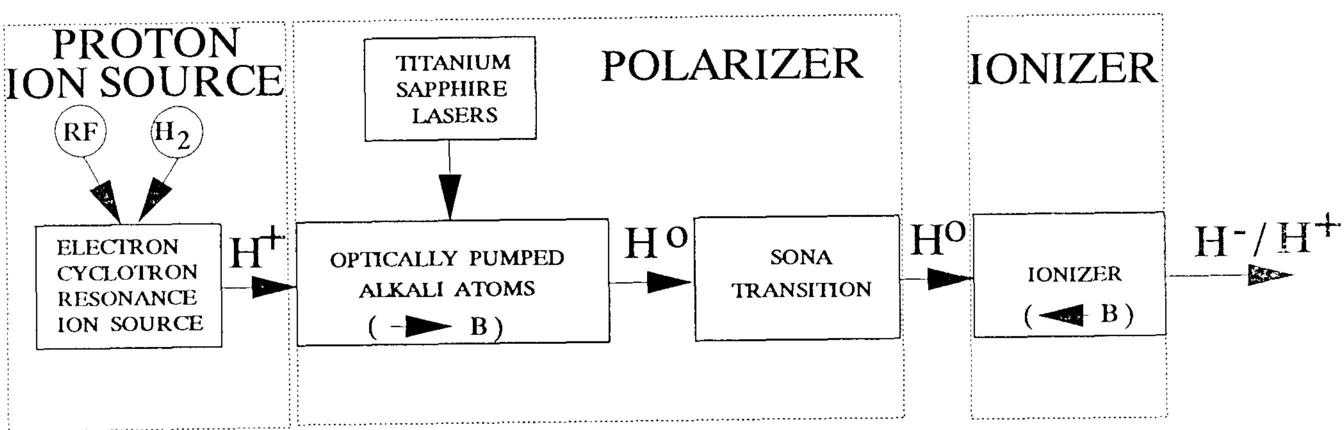

Fig. 4. A schematic of an optically pumped polarized ion source.

The performance figures of an OPPIS depend on the emittance and duty cycle of the ion beam. The current can be increased by opening apertures until the ion source emittance matches the accelerator acceptance. The efficiency for ionization to protons is about a factor of ten larger than the efficiency for ionization to H^- with the result that negative currents from the source are about a factor of ten less than positive currents. Both the current and the polarization also depend on the thickness of alkali vapour that can be polarized. The alkali thickness that can be polarized, in turn, depends on the power available from the lasers. Peak power from lasers can be substantially increased through pulsing. Thus for an accelerator (or for a particular experiment) requiring a pulsed polarized beam it is possible, under some conditions, to provide higher peak currents by matching the laser repetition rate to that of the accelerator (or experiment). For a given laser power, higher currents at lower polarization result from an increase in alkali thickness. With the TRIUMF source operating in a dc mode the measured nuclear polarization is about 61% @ 20 μA of H^-, 75% @ 10 μA, 78% @ 5 μA and 80% for low currents. These currents are for a normalized emittance estimated to be less than 0.7 π mm-mrad.

5. POLARIZED HEAVY ION SOURCES

An ion source for polarized beams of ^{6}Li, ^{7}Li and ^{23}Na was developed and used at Heidelberg.[10,11] An electron polarized beam was achieved by passing an unpolarized atomic beam through a Stern-Gerlach separation magnet (quadrupole). Subsequently, three sets of rf transitions were used to populate appropriate hyperfine states and provide various different vector and tensor nuclear polarizations. Positive ionization was achieved through surface ionization. These positive ions were converted to negative ions in a cesium vapour. With the use of lasers it is possible to pump alkali hyperfine states directly. This technique has yielded currents in the range of 2 to 6 μA and polarizations of about 80% for beams of ^{7}Li and ^{23}Na. Heavy ion polarized ion sources for cyclotrons are under development at the Institute for Nuclear Research in Kiev and at RCNP in Osaka.[12,13] The INR source is designed to provide polarized alkalies and is similar to the Heidelberg design. The RCNP source is of the OPPIS design and will be used initially to produce beams of polarized ^{3}He.

6. LOW ENERGY POLARIMETERS

In order to optimize a polarized ion source, efficiently, it is essential to have a dedicated on-line low energy polarimeter near the ion source. There is, in general, too much competition for accelerator time to allow adequate scheduling of the accelerator and its polarimeters for ion source optimization. Moreover, experience at TRIUMF has shown that the overhead, in terms of time and manpower, in preparing the cyclotron and high energy polarimeters is a significant fraction of the optimization process. At TRIUMF two different low energy polarimeters have been extremely useful. The first, a Lyman-α polarimeter, yields the polarization of protons in the energy range of 1 to 10 keV.[14] This polarimeter measures the asymmetric Lyman-α emission of photons by selective quenching of polarized hydrogen atoms excited to the 2S metastable states. Count rates are of the order of 0.5 MHz. This type of polarimeter is, in principle, suitable for deuterium beams. The second is a nuclear polarimeter based on the ^{6}Li(p,^{3}He)α reaction.[15] The analyzing power for detecting ^{3}He at 130° is approximately 0.21 at 300 keV. For deuterons the ^{3}H(^{2}H,n)^{4}He reaction has been used for energies around 100 keV.

7. CONCLUSION

Table I outlines the main performance characteristics of polarized sources which are either in use, suitable for use or being developed for use on cyclotrons. Caution must be exercised in interpreting the table as the best characteristics from a particular source are not necessarily all achievable simultaneously. The sources are frequently optimized to meet the needs of a particular accelerator or experiment and as such the emittance, polarization and/or resulting current may be different if the same source were optimized for a different accelerator. Much of the recent work on polarized internal targets overlaps and complements the work being done with sources. Two recent review papers provide an excellent overview of polarized ion source and related polarized target development.[16,17]

In summary, polarized ion source development remains a very active research endeavour and large improvements in source performance are still being realized.

8. REFERENCES

1) P. Schiemenz, Helv. Phys. Acta **59**, 620 (1986)
2) P. G. Sona, Energy Nucl. **14**, 295 (1967)
3) J. Benage, LANL report **LA-UR-85-4463**
4) W. Haeberli, Helv. Phys. Acta **59**, 513 (1986)
5) W. Greubler, KEK Report **90-15**, 56 (1990)
6) A. S. Belov *et al.*, KEK Report **90-15**, 69 (1990)
7) R. L. York, KEK Report **90-15**, 142 (1990)
8) C. D. P. Levy *et al.*, these proceedings
9) L. W. Anderson, Nucl. Instrum. Methods **167**, 363 (1979)
10) E. Steffans *et al.*, Nucl. Instrum. Methods **124**, 601 (1975)
11) D. Krämer *et al.*, Nucl. Instrum. Methods **220**, 123 (1984)
12) N. I. Zaika, these proceedings
13) M. Tanaka *et al.*, KEK Report **90-15**, 288 (1990)

Table I. A COMPARISON OF POLARIZED ION SOURCE PARAMETERS

PARAMETERS / SOURCES		LAMB-SHIFT	ATOMIC		OPPIS	(CHARGE EXCHANGE)	OPPIS DIRECT
POLARIZATION (%)	H^+	85	80[c]		≈ H^-		
	H^-	85[a]	80	95[d]	75[a]	61[a]	
CURRENT	H^+	1	150[c]		≈ 10 *	H^- current	
(DC μA)	H^-	1[a]	16	3[d]	10[a]	22[a]	
NORMALIZED EMITTANCE	H^+	0.3	< 1.2[c]		≈ H^-		
(π mm-mrad)	H^-	0.3[a]		0.35[d]	< 0.7[a]		
TENSOR POLARIZATION (% of maximum for D^+/D^-)		70[b]	85[c]	95[d]	not	suitable	
ONLINE POL'N ESTIMATE		yes	no		yes		
PARTICLES	H^+/H^-	yes	yes		yes		no
	D^+/D^-	yes	yes		vector	only	no
	$^3H^+/^3H^-$	yes	yes		yes		no
	$^3He^+$	yes	yes		yes		yes
	HEAVY IONS	no	yes		yes		alakalis
COHERENT INT. MODUL'N (%)			≈ $5 \cdot 10^{-5}$		≤ $5 \cdot 10^{-5}$ [a]		
P^2I (μA)	H^+	0.7	96		≈ 56.	≈ 80.	
	H^-	0.7	10	3	5.6	8.	
COMMERCIAL SUPPLIER		no	yes		no		no
RELATIVE COST		1	7 - 9		8		

[a] TRIUMF [b] Munich [c] PSI [d] Wisconsin

14) A. N. Zelenskii *et al.*, Nucl. Instrum. Methods **A245**, 223 (1986)

15) L. Buchmann, Nucl. Instrum. Methods **A301**, 383 (1991)

16) P. Schiemenz, Rev. Sci. Instrum. **63 (4)**, 2519 (1992)

17) T. B. Clegg, Conference Recored of the 1991 IEEE Particl Accelerator Conference, **Vol. 4**, 2083 (1991)