A REVIEW OF POLARIZED ION SOURCES

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The two main types of polarized ion sources in use on accelerators today are the Atomic Beam Polarized Ion Source (ABIS) source and the Optically Pumped Polarized Ion Source (OPPIS). Both types can provide beams of nuclearly polarized light ions which are either positively or negatively charged. Heavy ion polarized ion sources for accelerators are being developed.

I. INTRODUCTION

There have been significant advancements in the capabilities of polarized ion sources in the four years following the last review given to the Particle Accelerator Conference in 1991[1]. Polarized nuclei are an important nuclear physics probe and present day experiments require that the polarized ion source provide beams with high polarization, high beam current, exceptional beam quality and long term reliability. Although polarized ion sources have been in use for nearly 40 years, the development of enhanced ion source capabilities continues to be driven by the fact that the physics is fruitful and exciting.

New facilities will become available shortly in Japan, the Netherlands, Germany, China and South Africa. In addition, polarized ion sources are being upgraded with major modifications at a number of existing facilities. The possibility of accelerating polarized protons is being seriously examined for facilities such as RHIC[2] and FNAL[3]. Each of these accelerators has its own particular requirements and for optimal performance requires a unique polarized ion source. A number of recent review papers provide an excellent overview of polarized ion source design, development and operation[1,4,5,6].

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 (i.e., current intensity modulation correlated with spin flip) less than 1 part in 10^5 at a spin flip rate of approximately 100 Hz. In order to ensure that the experimental specifications are met for stability it is necessary for the source to produce at least 15 μA. Another experiment, at TRIUMF, examining pion production in *np* scattering used cyclotron slits to reduce, substantially, the cyclotron acceptance 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^-. This deliberate reduction in emittance to achieve the differing experimental requirements is realized by making the phase space cuts on different parts of the emittance and at different places in the acceleration process. The ion source must be capable of filling, efficiently, an acceptance which is larger than that required for one particular experiment. Many of the sources being built today are flexible and include the possibility to tailor the performance to meet an experiment.

There are a number of factors which must be taken into account in deciding the best polarized source for a particular accelerator. The experimental program 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, reliability and risk. The risk is often minimized by purchasing an ion source from a commercial company, if possible, in order to minimize the research and development required to meet the experimental requirements. With regard to statistical accuracy in an experiment, a commonly used figure of merit to compare the performance of the various polarized ion sources is given by P^2I, where P is the nuclear polarization and I is the current at the target.

Polarized ions are generally produced in an ion source comprised of four stages. 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. Occasionally as in the optically pumped proton polarized sources, these two steps may overlap. Next nuclear polarization is achieved by inducing transitions, from the occupied 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 this magnetic field (and therefore the effective transverse emittance) depends on the particular hyperfine states being ionized [7,8]. Table 1 lists the ‘advertised’ performance characteristics for a number of polarized ion sources selected for their unique capabilities.

Table 1 Performance characteristics for selected polarized ion sources

LAB.	TYPE	BEAM	DUTY CYCLE	IONIZER	EMITTANCE (π mm mrad)	POL’N (%)	CURRENT (μA)
INR	ABIS	H^+	0.0005	plasma	2.0	0.80	6000
ETHZ	ABIS	H^+	dc	ExB	1.2	0.85	400
INR	OPPIS	H^+	0.0001	Na vapor	0.8	0.65	4000
ETHZ	ABIS	H^-	dc	Na vapor			16
BNL	ABIS	H^-	0.0003	Cs beam	0.35	0.80	60
INR	ABIS	H^-	0.0003	plasma	0.23	0.70	500
TRIUMF	OPPIS	H^-	dc	Na vapor	0.8	0.85	150
TRIUMF	OPPIS	H^-	dc	Na vapor	2.0		1600
KEK	OPPIS	D^-	0.0014	Rb vapor		0.70	
KEK	OPPIS	D^-	0.0014	Rb vapor	2.0		380

II ATOMIC BEAM ION SOURCES

In an atomic beam ion source (ABIS), hydrogen (or deuterium) atoms are generated, initially, in a dissociator by a radio-frequency discharge and then formed into a low-velocity (thermal) atomic-beam with the aid of a cooled nozzle and a system of skimmers. Tapered magnets (quadrupole, sextupole) are used to separate (Stern-Gerlach effect) and focus one set of hyperfine states (with the electron spin aligned to the magnetic field) from the other set of hyperfine states (with the electron spin aligned in the opposite direction). Transitions between hyperfine states are induced by applying appropriate radio-frequency fields. These transitions are chosen to transform the separated atomic states which now have a similar electron spin direction (electron polarization) to hyperfine states of similar nuclear polarization. Frequently a second set of separation magnets is used to select a single hyperfine state. The beam of atoms in the selected state(s) are then ionized for ion acceleration or used as polarized atoms in experimental targets.

There are a number of approaches being used to ionize the nuclearly-polarized atomic beam. To produce positively charged ions, an electron impact ionizer is frequently 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 limit the amount of polarized beam which can be matched into an accelerator. 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 (~5%) by the ECR ionizer[9]. The PSI source, for example, produces about 150 μA of dc positive beam with about 79% polarization within a normalized emittance of less than 1.2π mm-mrad. The ETHZ group has reported positive currents as high as 400 μA using an ExB ionizer within a normalized emittance of 1.2 π mm mrad[10]. To produce negatively charged ions, the positively charged ions are accelerated to about 5 keV prior to being directed through an alkali vapor target where about 7% of the positive ions are converted to negative ions by double charge exchange. The achieved intensity was 16 μA at ETHZ. 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 (60 μA of 0.80 polarization) of excellent emittance (~0.35 π mm-mrad normalized by βγ)[11]. At the INR in Moscow, very high currents (~6 mA) have been achieved (albeit with 100 μS long pulses at a 1 Hz repetition rate within a normalized emittance of 2π mm-mrad) by making use of the larger charge exchange cross-sections of $^2H^+$ (compared to electrons) in a plasma to ionize directly the polarized atoms[12]. A similar arrangement at INR with the exception that the source was modified to make use of charge exchange with $^2H^-$ (instead of $^2H^+$) has recently yielded a peak current of 500 μA of negatively charged hydrogen ions in a 200 μs pulse[13]. A polarization of approximately 70% within a normalized emittance of approximately 2.3 π mm mrad is reported by the INR group.

The neutral beam intensity at the ionizer entrance (and consequently the source current) should improve as the beam velocity (temperature) is reduced. The predicted gains in polarized currents which should result by cooling the nozzle were not obtained, initially. The source must be treated as a whole and when the atomic beam velocity is changed, the magnet systems must be re-matched to this new velocity distribution. As the result of improved (reliable) computer tracking programs and the use of high field permanent magnets, it has been possible to realize a gain of 2 in the polarized atomic beam flux at Madison and at Heidelberg[14]. It appears, from results obtained at BNL that additional increases by further lowering the beam velocity will not provide further significant increases in atomic beam flux since intrabeam scattering prevents the atomic flux from substantially exceeding the 10^{17} atoms/cm^2/sec already achieved by the best sources[11]. Intrabeam scattering becomes a more severe problem as the temperature (beam velocity) is reduced.

Atomic beam polarized ion sources have been used for over 35 years and are being used successfully in many laboratories including; BNL, Bonn, Dubna, ETHZ, IUCF, INR, Julich, PSI, Saclay, TUNL, University of Washington and the University of Wisconsin. New sources are planned or being commissioned at IUCF, KVI, NAC (South Africa), RIKEN and Uppsala. Similar technology is used/planned for polarized gas targets at Dubna, Heidelberg, Madison, Novisibirsk, UNK and CERN.

In general, a higher peak current is obtained from sources with a small duty cycle. The INR plasma ionizer is very efficient, ionizing nearly all of the atomic beam. The difference in current between dc and pulsed ion sources is not due to the physics per se but rather a consequence of technology limitations and the larger current could, in principle, be achieved by steady state sources given the correct technology and financial resources. Negative beams tend to be at least an order of magnitude smaller than positive beams for a given ion source. Each source has been designed to be compatible with a particular accelerator or particular type of experiment and consequently does not have the same hardware nor the same emittance.

III OPTICALLY PUMPED SOURCES

A review of the status of optically pumped polarized ion sources in 1993 has been given by Mori[15]. The optically pumped polarized ion source (OPPIS) is based on a proposal by Anderson[16]. Lasers are used to achieve electronic spin alignment in an alkali vapor. 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) vapor at 795 (770) nm. Protons are directed at an energy of about 2 to 5 keV through the polarized vapor where by charge exchange they can pick up a spin aligned electron. The charge exchange process must take place in a large magnetic field (~ 2.5 T) in order to preserve the spin alignment. After removing any charged particles by means of transverse electric fields , the beam emerging from the alkali vapor is a neutral atomic hydrogen beam (at energy 2 to 6 keV) with two hyperfine states (of similar electronic spin) predominately occupied. This fast neutral beam has a number of advantages compared to the thermal ABIS beam. 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. Because of the higher velocity atomic beam in an OPPIS compared to an ABIS, alkali ionizers can operate at a sufficient thickness to realize an equilibrium fraction of negative ions, by double charge exchange, without a substantial emittance increase due to scattering.

Optically pumped polarized ion sources, based on charge exchange, have been developed at INR[17], LAMPF [18], KEK[19] and TRIUMF[20]. The performance of the OPPIS source is improving rapidly. It has been only 12 years since the first OPPIS at KEK[21]. 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 vapor 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 (by low energy polarimeter) is about 0.85 @ 150 μA of H^- (at the source) within a normalized emittance of 0.8 π mm mrad and after some optimization a polarized H^- current of 1.6 mA within a normalized emittance of 2.0 π mm mrad was achieved[22]. At LAMPF, 0.77 polarization was measured at 2 μA, 0.64 @ 38 μA and dropped to 0.56 @ 50 μA. It is worth noting that the usual figure of merit, P^2I, increases with increasing current (over the above range) even though the polarization is decreasing.

The OPPIS, based on charge exchange, has limitations on the output brightness (current\emittance^2) as a result of the magnetic field required to preserve (decouple **L** & **S**) the electron polarization during charge transfer as well as due to the magnetic field of the ionizer which is needed to preserve the nuclear spin orientation. The charged alkali atoms are radially confined by the magnetic field and contribute to the space charge on the proton beam. It seems feasible, certainly for low duty cycle operation, to achieve much higher currents from an OPPIS. Using the neutral beam technology, initially developed for fusion research, it is proposed to develop an OPPIS which is conservatively estimated to yield a highly polarized 10 mA of H^- within a normalized emittance of 1.5 π mm mrad[22,23].

It has been proposed to avoid the space-charge problem by using spin exchange with a neutral hydrogen beam instead of charge exchange with a proton beam. The cross section for spin exchange is nearly an order of magnitude (for hydrogen atoms in the few keV energy range) smaller than for charge exchange. Consequently it is necessary to optically pump thicker targets. The availability of high power pulsed alexandrite lasers and titanium sapphire has made the technique feasible. Initial experiments at INR and TRIUMF have demonstrated a polarization of 0.5[24]. The cross section for spin exchange increases as the energy of the atomic hydrogen beam is decreased. Commercial cw titanium sapphire lasers should already be capable of polarizing a sufficiently thick rubidium vapor target for atomic hydrogen beams at thermal energies. The currents for spin exchange ion sources are estimated to be considerably larger than for charge exchange sources.

Another approach, described by Poelker[25] and Jones [26], is a combination of atomic beam techniques and spin exchange. The source uses a dissociator to produce hydrogen/deuterium atoms which are allowed to diffuse at thermal energies through a potassium vapor polarized by optical pumping. The electron spin orientation is transferred to the atoms by spin exchange collisions. A beam is formed from the atoms leaving the potassium spin exchange cell. The nuclear polarization of the hydrogen/deuterium atomic beam is then achieved by a combination of rf induced transitions and separation magnets in a scheme identical to that used in atomic beam polarized ion sources. The Argonne group have reported[23] intensities of 1.7 10^{18} atoms/s for hydrogen which is almost an order of magnitude higher than that for conventional atomic beam ion sources. Atomic polarization exceeds 0.8 at intensities less that 2.0 10^{17} and decreases as the intensity is increased. With the addition of high magnetic fields surrounding the optical pumped cell, nuclear polarizations of over 0.5 are achieved even at intensities of 1.6 10^{18} atoms/s.

The KEK group has reported a novel extension of the OPPIS technique to demonstrate vector polarized deuterium. To achieve this result, they also polarized the ionizer alkali by optical pumping and were able because of the Pauli exclusion principle to select either one of the two spins by controlling independently the electron spin alignment of the two alkali cells[27]. The KEK group has obtained a nuclear-spin vector polarized negative deuterium ion beam with a polarization of 0.7. This group has also recently demonstrated 380 μA of negative deuterium after some optimization[28].

IV HEAVY ION SOURCES

An ion source for polarized beams of ^{6}Li, ^{7}Li and ^{23}Na was developed and used at Heidelberg[29,30]. 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 vapor. 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[31,32]. The INR source is designed to provide polarized alkalis 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.

IV 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 most frequently used polarimeter, a Lyman-a polarimeter, yields the polarization of protons in the energy range of 1 to 10 keV[33] This polarimeter measures the Lyman-a 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 was developed at INR and is also being used at KEK and TUNL. The TUNL polarimeter uses a rf spin filter and is being used to determine both proton and deuteron polarization[34]. TRIUMF also uses a nuclear polarimeter based on the

^{6}Li(p,^{3}He)a reaction[35]. 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.

V CONCLUSION

Todays polarized ion 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. However, there are several general guidelines. First, for accelerators requiring polarized beams of negative hydrogen, the best choice is an OPPIS. Second, for accelerators requiring polarized beams of positively charged hydrogen, the best choice is not obvious. Third, for accelerators requiring vector polarized beams of negatively charged deuterium the best choice is an OPPIS. Fourth, for accelerators requiring beams of tensor polarized beams of deuterium the best choice, at present, is an ABIS. Much of the recent work on polarized internal targets overlaps and complements the work being done with sources. In summary, polarized ion source development remains a very active research endeavor and large improvements in source performance are still being realized.

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