PERFORMANCE OF A HIGH INTENSITY POLARIZED H$^-$ SOURCE ON THE BROOKHAVEN 200 MEV LINAC*

J. Alessi[†], B. Briscoe, O. Gould, A. Kponou, V. LoDestro, D. Raparia, J. Ritter, A.N. Zelenski, BNL; V. Klenov, S.A. Kokhanovski, V. Zoubets, INR, Moscow; M. Okamura, RIKEN

Abstract

A new optically pumped polarized H$^-$ ion source was installed on the BNL 200 MeV linac in 2000, and has operated very reliably for RHIC polarized proton running during two periods of approximately 3 months each. This source, originally from KEK, was upgraded at TRIUMF for higher intensity operation [1]. It typically produces 0.5-1.0 mA of polarized H$^-$, in 400 microsecond pulses, 1 Hz, with a polarization of 75-80%. The 35 keV beam from this source passes through a pulsed dipole, so one is able to interleave polarized and high current unpolarized beam pulses before injection into an RFQ. Transmission from the source to the end of the linac exceeds 50%. One is able to continuously monitor beam polarization at 200 MeV. The layout and performance of this new injection line is described, including transverse matching, and design features of the beamline for preservation of polarization.

1 INTRODUCTION

The first polarized proton collider run in RHIC took place from December, 2001 – January, 2002. Polarized protons were successfully accelerated to 100 GeV, and held with ~8-hour storage times. This successful commissioning was followed by a 5 week physics run.

Polarized H$^-$ ions for RHIC are produced at 35 keV in a new Optically Pumped Polarized Ion Source (OPPIS), accelerated to 750 keV in an RFQ, followed by acceleration in the 200 MeV linac. The beam is then injected and accelerated in the Booster synchrotron and AGS, before injection into RHIC at ~ 25 GeV. The new OPPIS gives a polarized H$^-$ intensity at the end of the linac which is ~ 30 times higher than was typically achieved from the old BNL atomic beam source, and exceeds the RHIC requirement by a factor of three. A new 35 keV low energy beam transport (LEBT) had to be designed to allow injection into the existing RFQ without interfering with high intensity, unpolarized beam operations, while preserving polarization and giving the desired vertical spin alignment.

2 OPPIS SOURCE

The new OPPIS source was developed in a collaboration between Brookhaven, KEK, INR (Moscow), and TRIUMF. It is based on components from the KEK OPPIS, and was upgraded at TRIUMF for high current operation before being shipped to BNL in the fall of 1999. Some key features of the source are briefly described here, while more details can be found in [2]. The source has a 115 cm long superconducting solenoid with three separately adjustable coils. An ECR source operating at 29 GHz, ~ 0.8 kW, sits in the solenoid in a resonant field region of 10 kG. It produces the primary proton beam of ~80 mA at an energy of ~3 keV, with a multi-aperture extraction system (120 holes). Also located in the solenoid, in a field of 27 kG, is a Rb vapor cell. This vapor is polarized via optical pumping using circular polarized light from a 1 kW, flashlamp pumped Cr:LiSAF laser. Protons are converted to polarized hydrogen atoms via pickup of a polarized electron from the Rb. These 3 keV atoms are then converted to H$^-$ by electron pickup in a Na vapor jet cell, located in a separate solenoidal field of 1.4 kG. The entire Na jet assembly is biased to a voltage of –32 kV, so the H$^-$ ions are accelerated to a final total energy of 35 keV while leaving the source, for injection into the RFQ.

While an OPPIS very similar to this is operating dc at TRIUMF, and essentially all components of this source except the laser were operating dc when first delivered to BNL, we require only very low duty factor operation (< 0.5%). Therefore, the ECR source is now primarily operated with pulsed rf, and the extraction high voltage is also pulsed. This seems to have resulted in some improvement in reliability, and reduced significantly the loss of Rb vapor (coming from Rb$^+$ ions escaping).

The biasing of the Na ionizer cell at high voltage was a new development which simplified source installation considerably, since it avoided the need to have the entire source sit on a high voltage platform. This has proven to be a reliable solution, in large part due to the development of a new jet-type Na cell for the BNL OPPIS. This cell has low Na loss, despite the large aperture required to avoid primary beam, which is collimated externally to 2 cm diameter, from hitting the walls of the cell. The reservoir is loaded with 150 g of sodium metal, and both the reservoir and jet nozzle are operated at a temperature of 530 C. At this temperature the sodium vapor density is ~10^{17} atoms/cm^3, resulting in a vapor jet with an effective thickness of ~5 x 10^{14} atoms/cm^2, sufficient for saturation of the H$^-$ yield. The effectiveness of the recirculation is such that, although the entire 150 g circulates in ~3 hours, the cell provides continuous, stable operation for 1-2 months. The Na loss has proven to be much less than with the previous oven-type cell.

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[†] alessi@bnl.gov

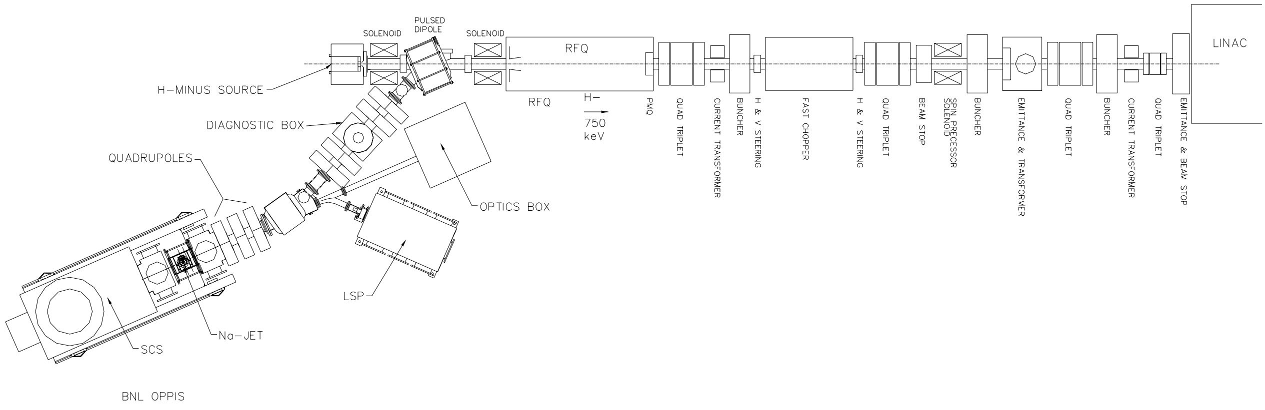

Figure 1: Schematic of the polarized beam LEBT and MEBT

3 LEBT DESIGN

It was decided to use the same RFQ for the new polarized ion source as is used for high current H^- operation (100 mA from a magnetron surface plasma source). Matching and injection into the RFQ from OPPIS could not interfere with that beamline, which uses two magnetic solenoids to focus the space-charge neutralized H^- beam into the RFQ, over a distance of 1.4m.

A layout of the LEBT is shown in Fig. 1. The only major change to the high current LEBT was that a diagnostic box located between the two focusing solenoids was removed, and replaced by a pulsed, 47.5^o dipole magnet. This dipole has a 10 cm gap, to prevent loss of beam from the high current line. The magnet can be pulsed in under 50 ms, which allows interleaving of high current and polarized beams through the linac on a pulse-to-pulse basis. In this way, high intensity beam can be delivered to the isotope production facility at the end of the linac between polarized beam pulses going to the Booster. (The linac control system allows switching of linac and transport line quadrupole settings, as well as buncher and accelerating cavity rf phase and amplitudes, on a pulse-to-pulse basis).

A second dipole had to be added after the OPPIS, and the bend angles were precisely chosen, in order to end with the desired vertical spin direction going into the linac. The beam is polarized in the longitudinal direction as it exits the source. The first dipole of 23.7^O rotates the spin by 90^O, making it perpendicular to the beam direction, in the horizontal plane. The second dipole, 47.5^O, rotates the spin by 180^O, so that it is again perpendicular to the beam direction, in the horizontal plane. After this bend, the beam is focused into the RFQ by the magnetic solenoid, which rotates the spin in the transverse plane by some amount ($\sim 420^O$), whose value is determined by the focusing required for proper matching into the RFQ. Following the RFQ, another magnetic solenoid was added, which has a minor effect on the 750 keV beam optics, but can be set to bring the spin back to the vertical direction. This solenoid is easily adjusted while measuring polarization in a polarimeter at 200 MeV.

Transverse matching into the RFQ is via a magnetic quadrupole triplet and two doublets, as shown in Fig. 1. Recently, the quadrupole triplet at the exit of the source has been replaced by an einzel lens. This was installed to try and “reject” a lower energy beam component, as described in Section 5, by operating the lens in the decelerating mode. It has the additional advantage, however, of being easier to tune than the triplet, while resulting in a transmission which is comparable to that measured with the triplet.

A pair of small horizontal and vertical dipoles allows slight steering of the beam without a significant effect on polarization direction.

More details on the design of this beam line can be found in [3]. As described there, 3D magnetic fields were calculated for the dipoles and focusing solenoid. The spin of particles was then calculated along with particle trajectories through the elements. It is estimated that there is only ~2% loss of polarization in the LEBT.

4 MEBT SPIN PRECESSOR & HEBT POLARIMETERS

The 750 keV beam transport from the RFQ to the linac was unchanged, except for the addition of a magnetic solenoid in an unused section of the line. This solenoid is identical to the two used in the 35 keV LEBT, and allows one to rotate the spin direction by an arbitrary amount in the transverse plane, in order to produce a final vertical polarization direction. The very slight effect on the transverse optics can easily be compensated for by adjusting several of the quadrupole triplets in the line, but it has been found to be unnecessary.

At 200 MeV, one can turn off the first dipole which sends the beam towards the Booster, and instead allow the beam to go to a downstream p-carbon polarimeter. This polarimeter, which has been used for more than 15 years, has been modified to handle the higher polarized beam currents we now achieve. With this polarimeter, we can get a 1% statistical precision measurement within 5 minutes. Typically, when polarized pulses were delivered to the Booster at a 0.2 Hz rep rate, a pulse would be sent to the polarimeter between Booster pulses, giving a continuous on line monitor of beam polarization. The p-C polarimeter was cross calibrated using a new p-deuteron polarimeter at the same location [4]. The analyzing power for p-d elastic scattering is very precisely known, but the cross sections are several orders of magnitude lower, so long p-d runs were taken for calibration purposes.

5 PERFORMANCE

The BNL OPPIS produces in excess of 1 mA of polarized H^-, with the desired pulse width of ~400 μs. This current is measured on a Faraday cup after the first LEBT dipole, ~ 2m from the source exit. While the source was typically operating at a 1 Hz repetition rate during the RHIC commissioning runs, we have since demonstrated reliable operation at 6.7 Hz. Another recent improvement has been to better match the ECR cavity to the magnetic field. This has resulted in an increase in source current to ~1.6 mA.

Beam polarization has been 75-80%. One unexpected effect that is causing some reduction in polarization comes from the H_2^+ ion component extracted from the ECR along with the H^+. When these molecular ions break up, with half the 3 keV H^+ energy, they can be ionized in the Na cell, resulting in a 33.5 keV H^- component along with the 35 keV H^- beam. This lower energy component has low polarization. It has been shown both in simulations and experimentally that under many conditions the LEBT tune will match both energy components into the RFQ, resulting in a reduced beam polarization. One attempt to increase the separation of these components was to switch to einzel lens focusing at the source exit. This seems to have resulted in the achievement of P>80% more routinely, but our experience is so far limited. In addition, H_2^+ output from the ECR is reduced in pulsed operation, and in dc operation an O_2 admixture reduces the molecular ions.

The source emittance is calculated to be 2.3 π mm-mrad (normalized, 100%) [3]. This emittance is essentially fully determined by the fact that the ions are produced over a 2 cm diameter in a 1.4 kG magnetic field. With some additional emittance growth expected in LEBT, we exceed the RFQ design acceptance, and the estimated RFQ transmission is 75-85%. We can not measure only RFQ transmission, but transmission from the middle of the LEBT to the linac entrance, 6m after the RFQ, is 60-70%. Linac transmission is typically 75-80%, and the total transmission from the source to 200 MeV typically exceeds 50%. Fig. 2 shows a beam pulse out of the source, and at the exit of the linac. This output exceeds our design goal for RHIC by a factor of three.

The extraction of the beam from the strong solenoidal field results in severe coupling of the beam in the horizontal and vertical planes. The complication resulting from this coupling is easily seen when observing the beam on a phosphor screen located in the diagnostic box in the middle of the LEBT. Here one sees complex beam spots, which are very sensitive to the ionizer solenoid setting and upstream lens and dipole settings. In addition, there are effects on the beam spot from source parameters such as pulsed vs. dc operation. To date, our modeling of this source/LEBT optics has been unsatisfactory. In spite of this, we routinely achieve our original goal of 50% transmission from the source to 200 MeV, and empirical tuning is fairly easy, with a variety of "acceptable" tunes.

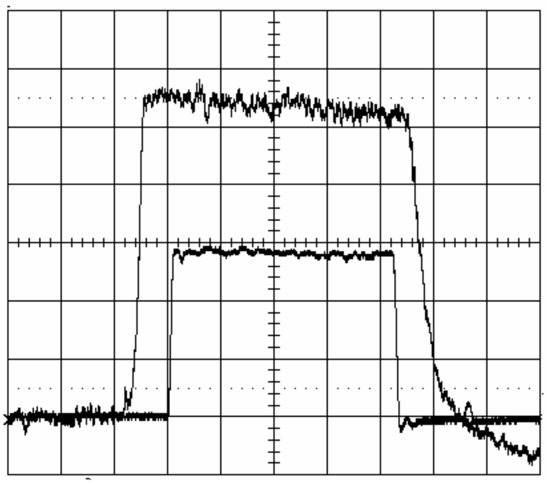

Figure 2: Polarized H^- ion current pulse: top trace at 35 keV; bottom trace at 200 MeV. 0.2 mA/div, 100 μs/div.

6 CONCLUSIONS

The new BNL polarized source now produces about 3 times our design goal for intensity meeting RHIC requirements. It easily produces >1 mA of H^- with polarization in excess of 75%. 50% of the source output is transported to 200 MeV. The source produces very flat beam pulses, and is very stable. It has been able to operate for 2 weeks between scheduled maintenance periods, and maintenance can sometimes be "transparent" to the RHIC spin program when done during an 8 hour period of stored beam.

7 REFERENCES

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