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The RHIC polarized source upgrade

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Abstract. The RHIC polarized H^- ion source is being upgraded to higher intensity (5-10 mA) and polarization for use in the RHIC polarization physics program at enhanced luminosity RHIC operation. The higher beam peak intensity will allow reduction of the transverse beam emittance at injection to AGS to reduce polarization losses in AGS. There is also a planned RHIC luminosity upgrade by using the electron beam lens to compensate the beam-beam interaction at collision points. This upgrade is also essential for future BNL plans for a high-luminosity electron – proton (ion) Collider eRHIC.

1. Polarized proton beams in AGS and RHIC

The polarized beam for RHIC spin physics experimental program is produced in the Optically-Pumped Polarized H^- Ion Source (OPPIS) [1]. The present RHIC OPPIS produces 0.5-1.0 mA (maximum 1.6 mA) current in 400 µs pulse duration. The polarized H^- ion beam (of 35 keV beam energy out of the source) is accelerated to 200 MeV in a linear accelerator for strip-injection to Booster. The H^- ion pulse is captured in a single Booster bunch which contains about $4 \cdot 10^{11}$ polarized protons. The single bunch is accelerated in the Booster to 2.5 GeV beam energy and then transferred to the AGS, where it is accelerated to 24.3 GeV for injection to RHIC. RHIC is the first collider where the "Siberian snake" technique was very successfully implemented to suppress the resonance depolarization during beam acceleration in AGS and RHIC [2]. A luminosity of a $1.6 \cdot 10^{32}$ cm^{-2} sec^{-1} for polarized proton collisions in RHIC will be produced by colliding 120 bunches in each ring at $2 \cdot 10^{11}$ protons/bunch intensity.

The RHIC polarized H^- ion source is being upgraded to higher intensity (5-10 mA) and polarization by using a very high brightness fast atomic beam source developed at BINP, Novosibirsk. This beam will be used in the RHIC polarization physics program at enhanced luminosity RHIC operation. The higher beam peak intensity will allow reduction of the transverse beam emittance at injection to AGS (by scraping of beam tails) to reduce polarization losses in AGS. There is also a plan the RHIC luminosity upgrade by using the electron beam lens to compensate the beam-beam interaction at collision points. This upgrade is also essential for future BNL plans for a high-luminosity electron – proton (ion) Collider eRHIC. In addition, the feasibility of high intensity (a few hundred mA) high brightness unpolarized H^- ion beam production in charge-exchange of high-brightness atomic hydrogen beam in sodium-jet ionizer cell will be studied.

The OPPIS initial longitudinal polarization is converted to the vertical direction, when the beam passes the 23.7 deg bending magnet and Spin Rotator solenoid in the Low Energy Beam Transport (LEBT) line (35 keV). The AGS cycle for polarized beam operation is 3 seconds, while OPPIS usually operates at a 1 Hz repetition rate. Pulses not sent to the Booster are directed by a pulsed bending magnet in the high-energy beam transport line to the 200 MeV p-Carbon polarimeter for spin-rotator tuning and continuous polarization monitoring. The Linac is operated at a 7 Hz repetition rate and six of the seven pulses from high-current un-polarized H^- ion source are used in radioisotope facility. This source is a surface production (Cs coated cathode) magnetron type. It routinely produces about 120 mA peak H^- ion current in a 500 us pulse. The un-polarized source is situated at the LEBT side line and the beam is directed to RFQ by the pulsed bending magnet, which is turned off for the polarized beam pulse.

The injector was upgraded for the 2009 polarized run. The RFQ was moved closer to LINAC and the MEBT (750 keV) beam line was rebuilt to improve RFQ to Linac beam matching. The spin-rotator was moved from the 750 keV line to the 35 keV line to align the spin to the vertical direction before injection to the RFQ. The final beam focusing into the RFQ was produced by the solenoid lens, which works better for high-intensity beam (to preserve a space–charge compensation), but introduced strong (about 270 deg) spin precession. A new combined function focusing lens in front of RFQ was built for 2011 Run. In this lens a pulsed Einzel lens is inserted in a new pulsed focusing solenoid of a larger 6.0" diameter. The Einzel lens is triggered on polarized beam pulse and solenoid lens is used for high-intensity un-polarized H^- ion beam focusing. This eliminated the spin precession in the focusing lens and allowed good transmission for the high-intensity beam. In addition a double Einzel lens system was installed, which works as beam velocity filter (see the details below). The upgrade resulted in reduced spin precession, better optics matching between RFQ and Linac and reduced the emittance degradation in the Linac (in both transverse and longitudinal phase space).

A new polarimeter for absolute proton beam polarization measurements at 200 MeV to accuracy better than ±0.5% has been developed as a part of the RHIC polarized source upgrade. The polarimeter is based on the elastic proton-carbon scattering at a16.2° angle, where the analyzing power is large 99.35% and was measured with high accuracy [3].

2. OPPIS upgrade with the Atomic Hydrogen Beam Injector

The ECR proton source is operated in high magnetic field. It has low hydrogen gas consumption, which makes possible a dc OPPIS operation with intensity in excess of 1.0 mA. The proton beam produced in the ECR source has a comparatively low emission current density and high beam divergence. This limits further current increase and gives rise to inefficient use of the available laser power for optical pumping. In fact only about 15% of the electron-spin polarized hydrogen atoms produced in Rb cell is within the ionizer cell acceptance.

In pulsed operation, suitable for application at high-energy accelerators and colliders, the ECR source limitations can be overcome by using a high brightness proton source outside the magnetic field instead of ECR[4,5]. Following neutralization in hydrogen, the high brightness 6.0-10.0 keV atomic H^0 beam is injected into a superconducting solenoid, where both a He ionizer cell and an optically-pumped Rb cell are situated in the 25-30 kG solenoid field, which is required to preserve the electron-spin polarization. The injected H atoms are ionized in the He cell with 80% efficiency to form a low emittance intense proton beam, which enters the polarized Rb vapor cell (see figure 1). The protons pick up polarized electrons from the Rb atoms to become a beam of electron-spin polarized H atoms (similar to ECR based OPPIS). A negative bias of about 3.0-7.0 kV applied to the He cell decelerates the proton beam produced in the cell to the 3.0 keV beam energy optimal for the charge–exchange collisions in the Rb and sodium cells. This allows energy separation of the polarized hydrogen atoms produced after lower energy proton neutralization in Rb vapor and residual hydrogen atoms of the primary beam.

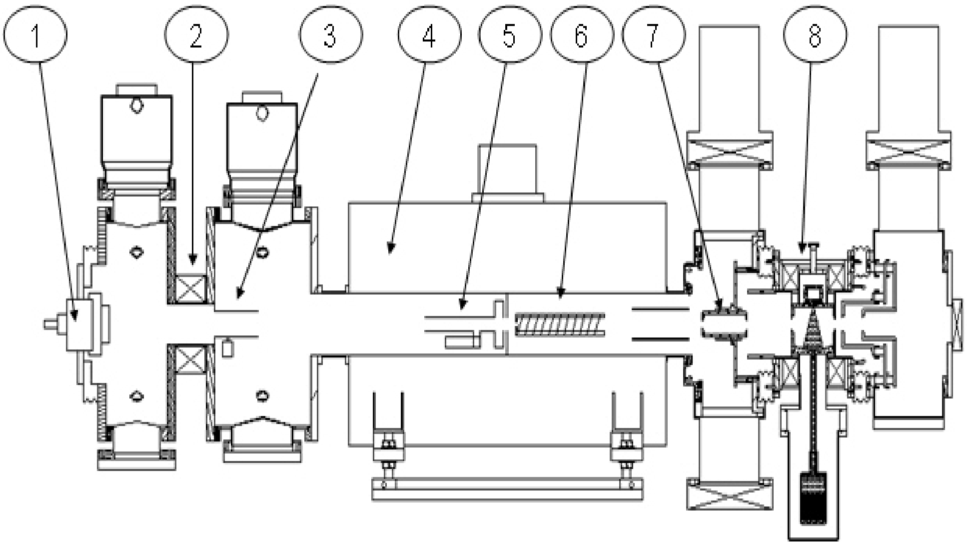

Figure 1: Layout of the OPPIS with atomic hydrogen injector: 1–high-brightness proton source; 2-focusing solenoid; 3-pulsed hydrogen neutralization cell;4- super conducting solenoid 30 kG; 5-Pulsed He ionizer cell; 6-optically-pumped Rb cell; 7-Sona shield; 8-sodium-jet ionizer cell.

Residual higher energy atoms will be neutralized with lower efficiency in Rb cell (due to cross-section decrease at higher energy) and un-polarized component will be further suppressed by lower H^- ion yield at 5.0-8.0 keV atomic beam energy. The H^- ion beam acceleration (by -32 kV pulsed voltage applied to the ionizer cell) will produce polarized H^- ion beam of a 35 keV beam energy and un-polarized beam of a 40-43 keV beam energy. Further suppression of un-polarized higher energy ion beam can be done in the LEBT.

Atomic hydrogen beam current of equivalent densities in excess of a 100 mA/cm^2 can be obtained at the Na jet ionizer location (about 200 cm from the source) by using a high brightness fast atomic beam source. This was tested in experiments at TRIUMF, where more than 10 mA polarized H^- and 50 mA proton beam intensity was demonstrated [5]. Higher polarization is also expected with the fast atomic beam source due to: a) elimination of neutralization in residual hydrogen; b) better Sona-transition transition efficiency for the smaller ~ 1.5 cm diameter beam; c) use of higher ionizer field (up to 3.0 kG). All these factors combined will further increase polarization in the pulsed OPPIS to ~ 90% and the source intensity to over 10 mA.

The RHIC polarized source upgrade for higher intensity and polarization is approved and funded for implementation in 2009-12. The source will provide the high intensity low emittance beam for polarized RHIC luminosity upgrade and for future eRHIC facilities.

3. Charge-exchange collisions. Beam energy optimization

The sequence of charge-exchange collisions in the OPPIS with atomic hydrogen injector is presented schematically in Figure 2 (for 10 keV primary beam energy). The primary beam energy optimization is an important part of this development. Higher intensity and lower proton beam divergence can be obtained at higher beam energy. The neutralization efficiency in hydrogen cell is about 95% for energies 6-10 keV. There is a molecular H_2^+ component (of about 5-10%) in the extracted beam, which is dissociated in collisions with hydrogen in neutralizer cell producing atomic beam of one half (3-5 keV) beam energy. The ionization efficiency in He-ionizer cell is 80% at 6 keV and 60% at 10 keV beam energy. The proton beam produced in the He cell is decelerated to 3.0 keV by the negative potential 3-7 keV applied to the cell (see figure 3).

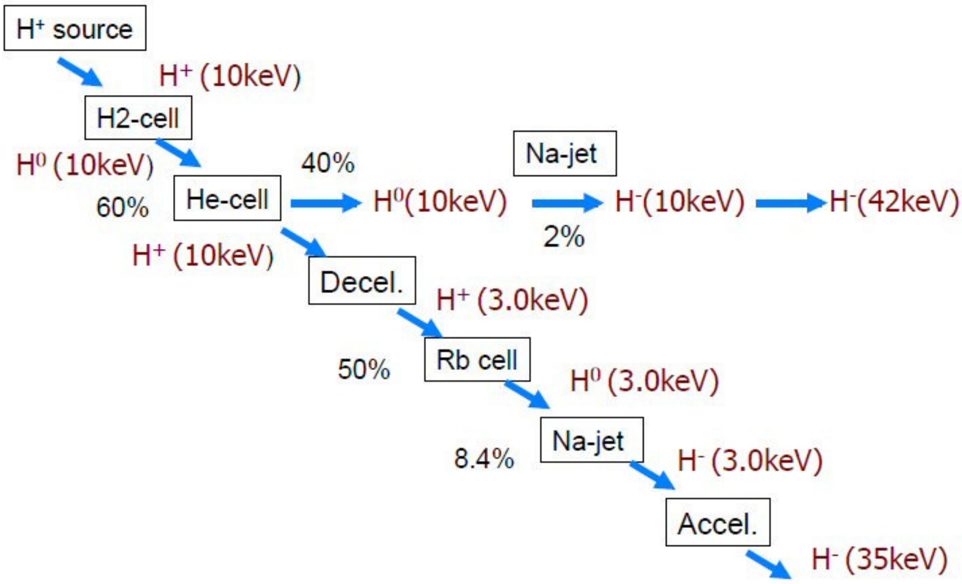

Figure 2: A chain of charge-exchange processes in OPPIS with Atomic Beam Injector. The energy of the primary proton beam is 10.0 keV.

At the 3.0 keV beam energy the H^- ion yield in the sodium ionizer cell is near maximum (~ 8.4%) and cross-section of polarized electron capture cross-section from Rb atoms is near maximum (~ 10^{-14} cm^2) too. The deceleration is produced by precisely aligned (to reduce beam losses) three-grid system. A small negative bias will be applied to the first grid and cylindrical electrode at the cell entrance to trap electrons in the cell for space-charge compensation. The expected beam losses at the grids should not exceed 5-10%. The beam divergence increase and associated losses will be studied experimentally.

About 40% residual (which passed the He-cell without ionization) atomic beam component of 6-10 keV energy will pass deceleration system, Rb cell (almost unaffected) and ionized in Na-cell producing H^- ion beam. The H^- ion yield at 6 keV is about 5% and at 10 keV it is ~ 2%. This is a significant suppression in comparison with main 3.0 keV beam, but it would be a strong polarization dilution unless further suppression is applied.

The H^- ion beam of 3.0 keV energy produced in the Na-jet ionizer cell is accelerated at the exit of cell to 35 keV beam energy by a 32 kV negative pulsed potential applied to the cell (see Figure 4, Ref.[5,6]). The 6-10 keV un-polarized H^- ion beam component is accelerated to 38-42 keV energy. An effective velocity "filter" was developed for suppression of this "wrong" beam energy components.

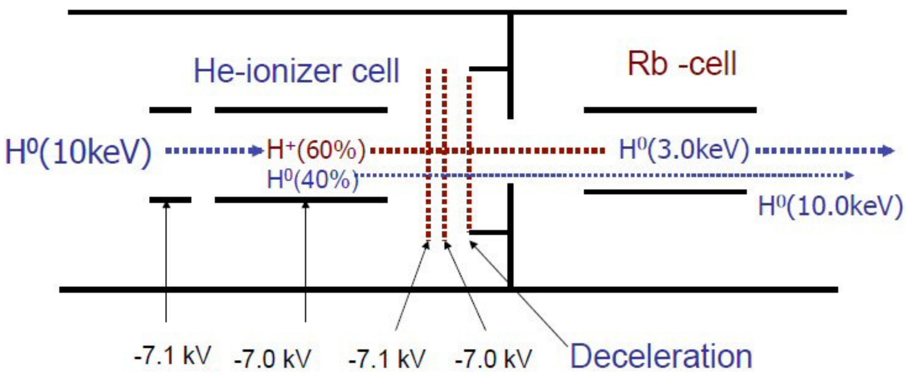

Figure 3: A schematic layout of the He-ionizer cell and deceleration of the proton beam for the energy separation of the residual un-polarized beam component.

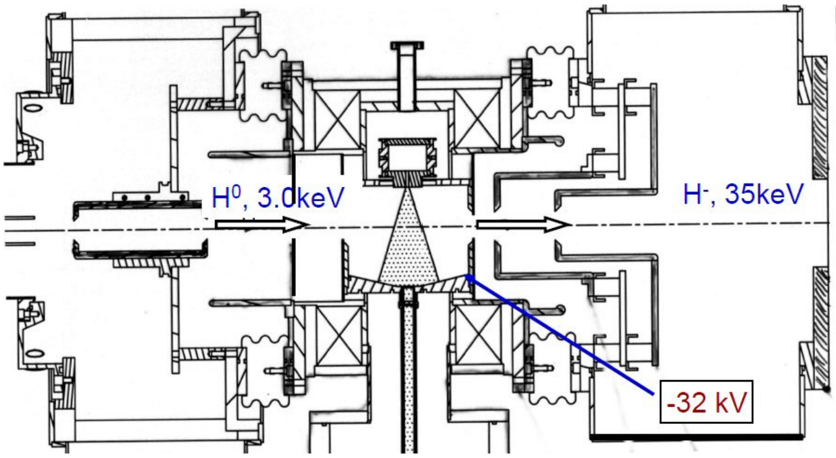

Figure 4: Beam acceleration after the ionization in the Na-jet ionizer.

The "filter" was developed for suppression of the lower 33.5 keV beam energy component produced at dissociation of molecular ions in the ECR primary proton source. The "filter" is a double Einzel lens system, which was installed in the OPPIS LEBT. A negative potential of about 35 keV is applied to the first lens. This potential decelerates and retards the lower energy (un-polarized) beam component. The second Einzel lens is tuned to compensate the strong focussing of the first lens for optimal beam transmission further for injection to RFQ. This velocity "filter" suppresses not only low energy but also higher energy beam components. The beam transmission vs. beam energy after tuning optimization is shown in Figure 5. The suppression factor exceeds order of magnitude for the beam energy difference 2 keV. For energy difference 7 keV the estimated suppression will be about 100 times and polarization dilution should be less than 0.3 %.

At 6.0 keV primary beam energy the dissociation of molecular H_2^+ ions will produce 3.0 keV atomic hydrogen beam. About 20% of this beam will pass the He-cell without ionization and will be converted to H^- ion beam of the same energy as main polarized beam (no further suppression can be applied in the LEBT). In assumption that H_2^+ from the source is about 5% the polarization dilution would be 2.5%. The use of higher energy 10 keV beam would be beneficial since higher energy 5 keV beam is produced after dissociation and dilution component energy is 37 keV. This 2 keV difference is sufficient for ten-fold suppression by double EL system in LEBT and polarization dilution can be reduced to 0.25%.

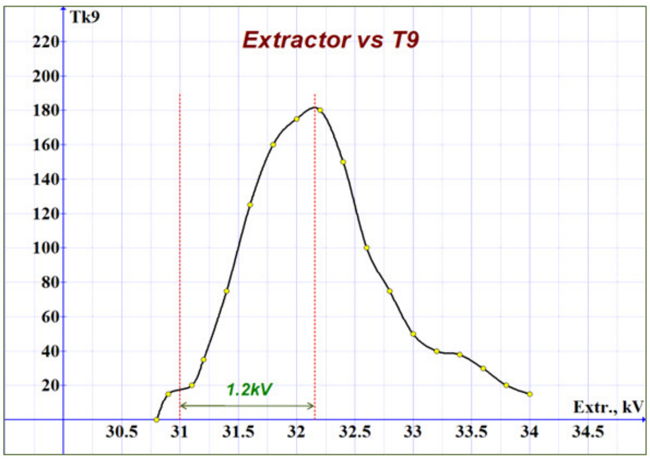

Figure 5: H^- current out of Linac vs. extraction voltage applied to the Na-jet cell.

4. Atomic beam source development

The atomic beam injector is under development at BINP, Novosibirsk. In this injector the proton beam is produced by a four-grid multi-aperture ion extraction optical system and neutralized in the H_2 gas cell downstream from the grids (see figure 6). A high-brightness atomic hydrogen beam was obtained in this injector by using a plasma emitter with a low transverse ion temperature of ~0.2 eV which is formed by plasma jet expansion from the arc plasma generator [7]. The multi-hole grids are spherically shaped to produce "geometrical" beam focusing [8]. The grids are made of 0.2 mm thick molybdenum plates. Holes in the plates (of a 0.4 mm in diameter) were produced by photo-etching techniques. An array of 7466 holes is forming a hexagonal structure with the step of 0.55 mm and outer diameter of 5.0 cm. The grids were shaped by re-crystallization under pressure at high temperature. The grids are welded to stainless steel holders by pulsed CO_2 laser. The elementary cell of this four electrode ion optical system (acceleration-deceleration type) was optimized by the PBGUNS code [9]. At emission current density of a 470 mA/cm^2 an angular divergence of the produced beam is ~ 15 mrad.

The focal length of the spherical ion extraction system was optimized for OPPIS application, which is characterized by a long polarizing structure of the charge-exchange cells and small (2.0 cm in diameter) Na-jet ionizer cell, which is located at a 240 cm distance from the source (see Figure 1).

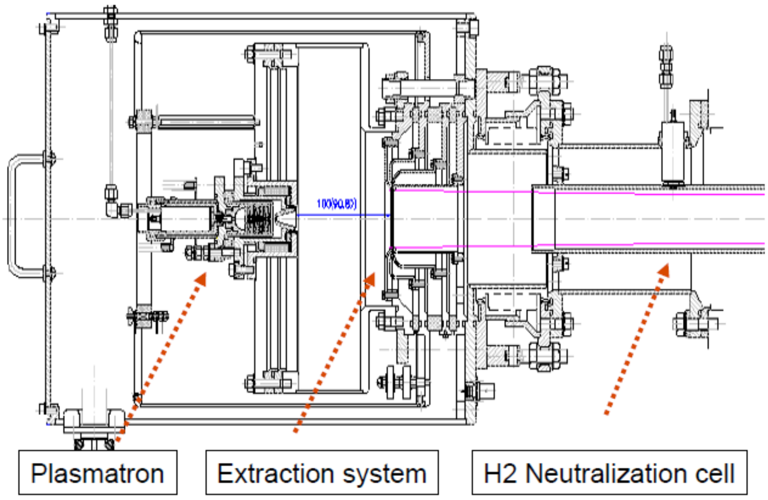

Figure 6: Atomic beam injector with geometrical focusing.

An optimal drift-space length of about 130 cm is required for convergence of the 5 cm (initial diameter) beam to 2.5 cm diameter He-ionizer cell. After ionization in the He-cell the proton beam gyro-center is not moving radially, while the ions travel in uniform magnetic field inside the solenoid, and proton velocities remain the same. Therefore, the protons do not experience any angular divergence for about 70 cm from the end of the He ionizer cell to the end of the solenoid and the magnetic field conserves the current density profile and the beam angular divergence. After the solenoid the divergence becomes larger due to addition of the randomized regular radial motion to the initial inherent divergence of the emitter, but the 40 cm distance to the Na-jet cell is relatively short, and the resulting ion beam expansion remains acceptable. Thus, in the given geometry the effect of the "current density conservation" in the magnetic field occurs to be stronger than the increased angular divergence after the solenoid. With the magnetic field the total current through the Na-jet cell is by a factor of 2.3 larger than the current in the absence of magnetic field in the same geometry (see figure 6).

About 10% (of total neutral injector current of a 4 A) can be transported through the Na-jet cell acceptance (with the magnetic field) by using optimal extraction grid system of a focal length:

$F \approx 200$ cm. Taking into account ionization efficiency in He-cell of a 60%, polarized electron capture in the Rb-cell of a 50% and H^- yield in the Na-jet cell of a 8.4% the expected polarized H^- ion beam current is expected to be ~ 10 mA. The beam deceleration after the He-cell may introduce some additional beam losses, which will be studied experimentally.

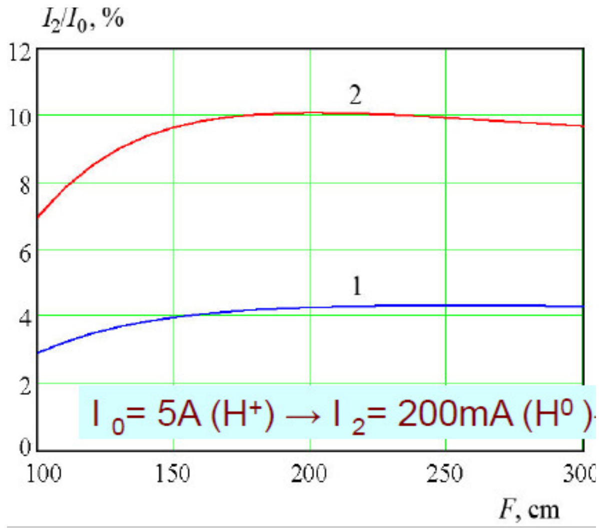

Figure 7: Ratio of the target current to the emitter current vs. focal distance: 1 – without magnetic field; 2 – with magnetic field.

5. Superconducting Solenoid development

A new super-conducting solenoid is being constructed for the OPPIS upgrade. This is a persistent current solenoid with cold iron yoke and, a 154 mm in diameter warm bore. The pulse tube cryocooler will provide cooling of the two layers of thermal shield and re-condense helium in the 50 l liquid He vessel. Five independently energized coils will allow of the solenoid operation in two different modes. In the Atomic Beam Mode with a 70 cm long 3.0 T flat-top will be produced for operation with neutral beam injection and He-ionizer cell as discussed above. In the ECR mode the field shape optimal for 29.2 GHz ECR-primary proton source operation [1] will be produced with an additional set of coils. The OPPIS performance improvement is expected with the carefully designed field shape optimized from experience of OPPIS operation. Installation and operation of the new solenoid is planned for 2012 Run in the ECR mode, while the development of the Atomic injector will be continued at the test bench.

6. Experimental results

Studies of the neutral beam formation and charge-exchange processes are presently in progress at the full-scale Test Bench, which is closely reproduce the OPPIS upgrade Layout (see figure 1) except the superconducting solenoid, which is replaced by a cylindrical vacuum chamber of 150 mm ID. A four electrode multi-wire ion optical system developed for experiments at TRIUMF [5] was initially used for these studies. The proton beam of 3-7 keV energy and total current of 3-6 A is focussed by solenoid lens and then is neutralized in the pulsed hydrogen target. Atomic hydrogen beam is ionized in the Na-jet cell and is deflected by bending magnet and measured by the Faraday cup in the diagnostic box. The maximum H^- beam current of a 12 mA at 7 keV beam energy was obtained in these experiments (see figure 7). Taking into account that H^- ion yield is ~ 4 % at energy 7 keV the total equivalent neutral hydrogen beam intensity was estimated at 300 mA. The estimated angular divergence of the formed atomic beam (from beam profile measurements by the secondary emission monitor) was ~15 mrad normalized emittance of the produced H$^-$ beam is estimated as 0.15 cm·mrad, as expected.

The H$^-$ current is increasing with energy due to higher source current and smaller beam divergence in spite of H$^-$ yield reduction in Na-cell with energy. Magnetic beam focusing at low beam energies was studied in BINP and TRIUMF experiments [5]. These experiments have shown that at energy below 4 keV the magnetic focusing of ion beam is reduced due to insufficient beam space charge compensation by secondary electrons in the magnetic lens. At present a new extraction system with spherical grid and geometrical focussing was delivered from BINP for beam formation studies and experiments are in progress to assess the extraction system performance and optimization.

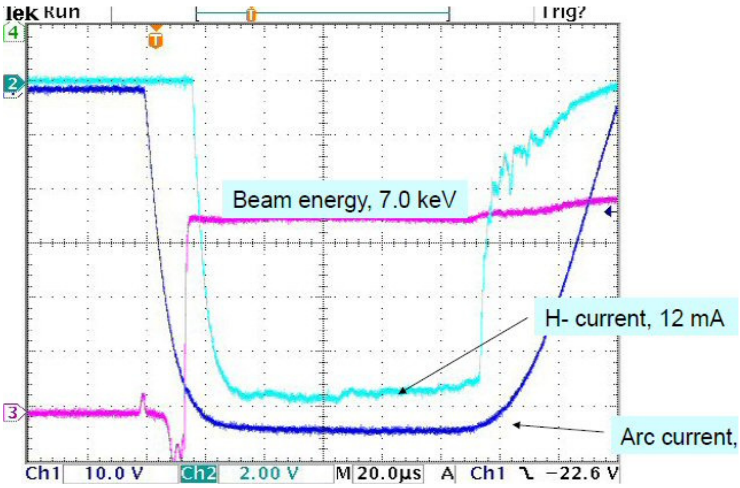

Figure 7: Oscillogram of the H$^-$ ion current, arc current (600 A), and extraction voltage pulse (7 keV).

7. Summary

Polarized H$^-$ ion beam current in excess of 10 mA is expected after the OPPIS upgrade with this Atomic Hydrogen Injector developed at BINP, Novosibirsk. Higher polarization is also expected with the fast atomic beam source due to: a) elimination of neutralization in residual hydrogen; b) better Sona-transition transition efficiency for the smaller ~ 1.5 cm diameter beam; c) use of higher ionizer field (up to 3.0 kG). The beam emittance will be kept below 2.0 π mm·mrad due to the smaller beam diameter. All these factors combined will increase polarization in the pulsed OPPIS to ~ 85-90%.

The RHIC polarized source upgrade for higher intensity and polarization is funded for implementation in 2009-12. The source will provide the high intensity low emittance beam for polarized RHIC luminosity upgrade and for future eRHIC facilities.

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