ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPML016

HIGH-INTENSITY MAGNETRON H⁻ ION SOURCES AND INJECTOR DEVELOPMENT AT BNL LINAC

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Abstract

The BNL magnetron-type H- ion source and the injector are being upgraded to higher duty-factor as a part of Linac intensity increase project [1]. The BNL magnetron source presently delivers 110 -120 mA H^- ion current with 650 us pulse duration and 7 Hz repetition rate. The pulse duration was increased to 1000 µs by modifications of the gas injector pulsed valve and the use of the new arc-discharge power supply (with the arc-current stabilization circuit) which improved current stability and reduced current noise. The Low Energy Beam Transport (LEBT) lines combine two beams. The first line is the polarized OPPIS (Optically Pumped Polarized H- Ion Source) beam-line and the second is the high-intensity un-polarized beam-line from the magnetron source, which transports beam to the RFQ after the passage of 45 degree bending magnet. The second magnetron source was installed in the straight LEBT section in 2017, in which the polarized OPPIS beam was not planned. In this, optimal for H^- beam transport configuration, the beam intensity was increased to 80 mA after the RFQ. The experience of the two sources layout operation (one source in operation the second source in standby) might be useful for facilities with the high downtime cost (like high-energy collider LHC or multi-user facilities like SNS).

INTRODUCTION

There are two types of high-intensity H^- ion sources in use at high energy and high average intensity accelerators. Surface Production ion Sources (SPS) are based on highly efficient H^- ion production in collisions of ions produced in hydrogen plasma with caesium coated molybdenum surface [2]. The characteristic features of these sources are: the high power efficiency (the 100 mA H- ion beam current is produced with less than ~ 2.0 kW arc-discharge power); high emission current density (of about 1.6 A/cm^2) and the small arc-discharge chamber volume, which enables the gas pulsing and greatly increases the source gas efficiency. These features make feasible high duty-factor operation. The ISIS Penning type SPS is operated with 5% duty factor (the 50 Hz and 1.0 ms arc-discharge pulse duration) [3]. The pulsed gas operation was implemented at the BINP, Novosibirsk source at 100 Hz repetition rate [4]. In contrast, the gas pulsing in the volume production H^- ion sources (with large volume of the plasma chamber) gives some gas flow reduction only at a low (~1 Hz) repetition rate. The low emission current density (of about 0.16 A/cm^2) requires a large (~ 7.0 mm in diameter) extraction system aperture. As a result, in SNS RF-driven H- ion source the gas consumption is very high about 30 sccm. This causes large beam losses due to the H^- ion beam stripping in residual gas and large gas load to the RFQ accelerator section. Nevertheless, the reliable long-term operation (up to 20 weeks) at 6% duty factor and 60 mA H-ion current (as measured at injection to the RFQ) was achieved at the SNS with internal RF antenna [5].

The magnetron surface plasma H^- ion source has been in use at BNL since 1982 after AGS upgrade with a rapid cycling Booster. A multi-turn strip injection of 200 MeV H^- ion beam into the Booster increased the AGS beam intensity to $5.0 \cdot 10^{13}$ protons/pulse. The AGS beam was used for experiments with high-intensity secondary mesons and neutrino beams. The charge-exchange multi-turn injection of the polarized H^- ion beams to the accelerator rings is essential for feasibility of experiments with polarized proton beams at high-energy accelerators and colliders because of polarized sources intensity is lower than for un-polarized sources. The RHIC complex is the first high-energy accelerator complex where the "Siberian snake" technique was successfully implemented to avoid resonance depolarization during beam acceleration in the AGS and RHIC and high-intensity polarized H^- ion source combined with the charge–exchange injection allowed to achieve maximum possible intensity and luminosity limited by the beam-beam interaction [6].

The high-intensity polarized H^- ion source was developed for the RHIC spin-physics program and incorporated in the Linac LEBT system in year 2000. At present, the LEBT combines two beams. The first beam–line is the polarized beam-line from the OPPIS and the second beam-line is the high-intensity un-polarized beam from the magnetron source, which transported to the RFQ after the passage of 45 degree bending magnet. This layout is a compromise in favour of the polarized beam transport efficiency, because of the increased length of the un-polarized beam transport and the bending magnet causes some beam losses. The space-charge compensation was improved by the xenon gas injection in the transport line and about 80 mA of H^- ion beam was transported to the RFQ input [7]. About 67 mA was accelerated in RFQ and 57 mA peak beam current was accelerated to 115-200 MeV beam energy in the Linac and delivered to the isotope production target. Since the first RHIC run in 2000 to the Run-2017 the polarized beam was the primary beam for the Linac operation. There was no plan to use polarized beam in the Run-2018. Therefore, we installed the second magnetron source in the straight LEBT section. In this, optimal for the H^- beam transport configuration, the beam intensity was increased to 80 mA after the RFQ and fast switching (in about 5 minutes) of the sources was successfully tested.

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BNL MAGNETRON H- ION SOURCE

As a result of the numerous improvements the BNL magnetron source routinely delivers 110-120 mA H- ion current in 650 µs pulse duration and 7 Hz repetition rate [8]. The beam extraction voltage is 35 kV. In the tests of the magnetron source for the possible use at the CERN Linac 4 injector the extraction voltage was increased to 40 kV and the beam intensity increased to 130 mA [9].

The arc-discharge current in the magnetron source is only 10-15 A and the arc-discharge voltage is a 140-150 V (see Figure 1). Therefore, the peak power of the arc-discharge is less than 2.0 kW for 100 mA H- ion beam current. This is comparable with the power efficiency of the best proton sources.

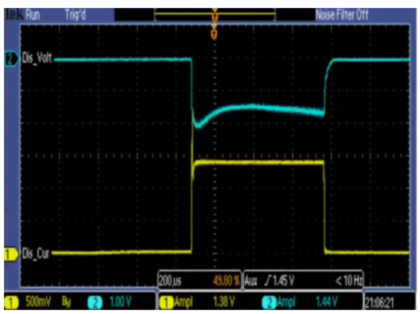

Figure 1: The magnetron arc-discharge operation. The yellow trace is the 14 A discharge current, the blue trace is the 150 V arc-discharge voltage.

The average arc-discharge power at 650 us pulse length and 7 Hz repetition rate is only about 10 W. Presently, there is no forced cooling in the source. We actually, we introduced some additional heating of the magnetron body to maintain it at about 160-180 ºC temperature for the optimal Cs distribution and the best source performance.

The magnetron source has a very small discharge volume (of about 1.0 cm^3) and the very high emission current density. The extraction aperture diameter is only 2.8 mm for the 100 mA beam. Therefore, the gas pulsing by the pulsed valve greatly increases the gas efficiency. At 7 Hz repetition rate and 100 mA H- ion beam current the total hydrogen gas flow was only 0.6 sccm. Simple scaling to 50 Hz repetition rate would imply less than 5.0 sccm gas consumption, which can be further reduced by the valve performance optimization and some reduction of the extraction aperture diameter.

NEW MAGNETRON OPERATION

The second magnetron source was installed in the straight LEBT section. While we used an identical (spare) magnetron body, a number of upgrades were implemented. The gas injection is very critical for optimal source operation. The pulsed valve operation is essential for the stable source operation at the best performance and the source gas efficiency. We used the original BINP, Novosibirsk valve as a prototype and made a number of improvements. The main improvement is the replacement of the rubber compression parts with the miniature springs. This change improved valve temperature stability and simplified valve assembly and tuning. The valve outlet hole was reduced to 0.13 mm. As a result, we obtained reliable valve operation and somewhat reduced total gas flow. We also developed a new power supply for the valve (with current stabilization and pulse duration control). This helped to increase pulse duration of the beam to 1000 us. We modified the system of heaters for the Cs supply to magnetron discharge chamber to ensure steady flow with minimal Cs consumption. The new arc-discharge power supply improved current stability and reduced the current noise. The average arc-discharge power is quite low ~10-15W, therefore we use additional heater for the magnetron body to maintain the magnetron body temperature at 160-180 ºC optimal for the magnetron operation. We built the complete new set of PS for the source. It is a very compact design just about 90 cm toll and placed in the bottom part of the source bench. At 7 Hz repetition rate we use just one turbo-molecular pump of the 1000 l/s pumping speed to operate the source. We modified the source ion optical system with the longer ceramic insulators and larger protection cups to reduce Cs and sputtered tungsten deposition to the insulators. The custom-made Macor insulators were replaced with conventional (inexpensive) ceramic insulators. This design eliminated leakages along the ceramic insulators, which developed after an extended operation and increased the extraction voltage operational range to at least 40 kV (maximum voltage of the power supply). The electron current is less than 50% of the ion current. It was measured as the difference between the total HV extractor power supply current and the H- ion beam current. The second modified magnetron source produced 120 ma H- ion current at 14 A arc discharge current (see Figure 2).

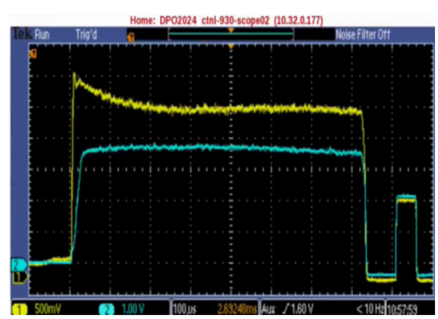

Figure 2: The second magnetron operation. The yellow trace is 120 mA source current as measured in the first current transformer after the source, the blue trace is 90 mA current at the entrance to the RFQ. The square pulse is the calibration 50 mA current pulse.

At 18 A arc-discharge current and at 36 kV extraction voltage, the source produced in excess of 120 mA current. About 110 mA current was transported for injection to the RFQ in the LEBT with the two focusing solenoids and 85-90 mA was accelerated to 750 keV in the RFQ (see Figure 3).

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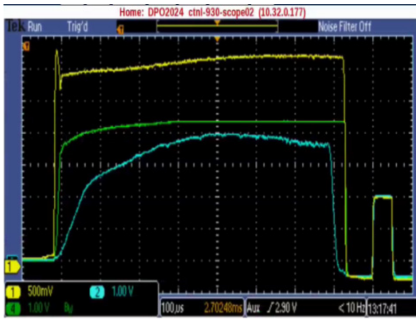

Figure 3: The source operation at 18 A arc-discharge current. The Yellow trace is the source current, the green trace is the current at injection to the RFQ and the blue trace is the current measured after the RFQ.

The gas injection into the LEBT line reduced the space-charge neutralization time to less than 50 us and increased the total integrated current by about 15 %. We used the pulsed electro-magnetic valve for the nitrogen gas injection. The best results were obtained at the optimal pressure in the LEBT of about $3 \cdot 10^{-6}$ torr.

We tested the feasibility of the source pulse length increase to 1000 µs for the ongoing Linac intensity upgrade with the longer pulse duration. The reliable long-term operation was demonstrated at arc-discharge current 10 A and H^- ion beam intensity 90 mA.

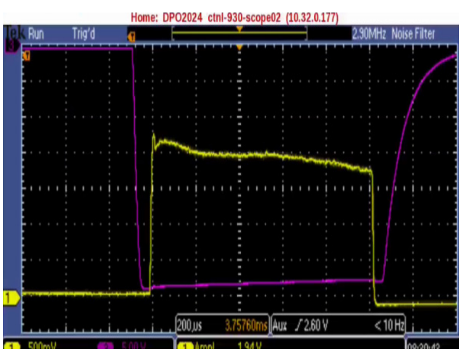

Figure 4: The long pulse operation of the magnetron source. The yellow trace is the 100 mA source current (the time scale is 200 us/div.). The magenta trace is the extractor voltage pulse.

The short-term operation at the arc-discharge current 14 A produced 100 mA current (see Figure 4), but the magnetron body overheating caused the unstable operation. We plan to introduce the additional cooling to maintain the magnetron at optimal temperature and ensure a reliable long-term operation. At present, the magnetron body is thermally insulated from the vacuum chamber flange by the Macor plate. This insulation will be reduced by the plate thickness reduction or replacement with the stainless steel plate. The heat load to the flange (of about 5 W) can be removed by the simple air-cooling.

NEW LEBT LAYOUT WITH THE THREE SOURCES

We plan to further upgrade the LEBT to combine two magnetron un-polarized sources beamlines and polarized source beamline before the final focusing to the RFQ. We already demonstrated the high-efficiency beam transport with the 45 degree bend and gas injection for the space-charge compensation. In addition, the 45 degrees bend removes the proton beam produced by the stripping of the H^- ion beam in residual gas. This injector layout with the short switching time between the two magnetron sources will be a good prototype for the injectors with the high cost of the downtime.

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