# INTENSE, HIGH BRIGHTNESS H⁻ BEAMS FROM SURFACE PLASMA SOURCES

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*Abstract*

High-current $H^-$ beams from a reliable surface plasma source are of great interests for spallation neutron sources and hadron colliders. At Maryland, $H^-$ beams have been studied using a magnetron and a Penning-type surface plasma source. Stable operating conditions with negligible beam noise have been achieved in both cases. The beam characteristics are much improved in the Penning geometry; the beam brightness is about an order of magnitude higher. An emission current density of ~ 1A/cm$^2$ with normalized beam brightness of $\gtrsim 10^{12}$A/(m-rad)$^2$ has been achieved. The minimum energy spread $\Delta E$ (FWHM) is measured $\lesssim$2.5eV. The actual $\Delta E$ is possibly much smaller since this value is close to the resolution of the energy analyzer. The results are sensitive to the beam noise, and the gas pulse is the key control parameter here. Long, stable operations with very limited source maintenance have been noted. So far, an emission aperture of diameter = 0.6mm is used when the $H^-$ beam current is $\gtrsim$ 2mA at 10kV. The beam current can be scaled to $\gtrsim$30mA for an emission aperture of diameter ~ 2.4mm. The critical issues for noiseless, high-brightness $H^-$ beams, the source performance, and the scaling of beam parameters are discussed.

## 1 INTRODUCTION

High-brightness ion beams are at the frontiers of many current research areas in basic and applied science including high energy accelerators, microelectronics, ion beam microscopy, and materials science. Many common physics and technology issues have been studied in the ion source development for these diverse applications. The present state-of-the art has been described in several articles [1-6], which clearly indicate the rapid pace of development in the field. Several national laboratories in the US including Los Alamos National Laboratory [7], Lawrence Berkeley National Laboratory [8], Oak Ridge National Laboratory [1,9], Fermi National Accelerator Laboratory [10] and Brookhaven National Laboratory [2], have been engaged over the years in advancing the frontier of ion source technology. However, this particular arena of research and development has been gaining renewed interests with the growing demands in the context of many new challenging programs, and therefore, new ideas and approaches are being attempted. One of the important major projects of current times is the Spallation Neutron Source program, where the critical needs of an ion source are highly emphasized. The executive summary of the workshop on spallation neutron sources indicates that the present state-of-the art of high-brightness ion sources falls short of the requirements for the program [11]. Depending on the power level of the facilities, being in the range of 1-5MW, the source peak current requirements vary from 40mA to about 150mA, and the duty factor is in the range of 1% to about 10%. The normalized emittance (90%) for typical beam current of 100mA needs to be $\lesssim$ 1mm-mrad (the factor of $\pi$ is excluded here), and the lifetime of the source should be ~ 1000 hours. It is highlighted in the workshop summary that $H^-$ beams from a surface plasma source (SPS), such as a Penning or a semiplanatron source, will be a good candidate for the pulsed spallation source scenarios currently under investigation.

At Maryland, efforts are made to develop high-quality surface plasma sources which have merits to satisfy the needs of both advanced accelerator applications and microfabrication. Experiments are being conducted with a Penning and a magnetron type SPS source, and the results are presented here. Note that the Penning source at Maryland has been operated so far using small extraction aperture with diameter = 0.6 mm, while beam characteristics have been studied for two sets of extraction apertures, one with a diameter of 2.5 mm and the other with a diameter of 0.5 mm, in the case of the magnetron source. These experimental results provide a good database for the performance characteristics of two SPS sources.

## 2 PENNING SOURCE AND H⁻ BEAM MEASUREMENTS

The geometrical characteristics of a Penning-type ion source, developed in Maryland in collaboration with the Budker Institute of Nuclear Physics, have been described elsewhere [12-13]. This source has been running reliably for more than eight hundred hours over the past one year with limited maintenance. The source runs in a pulsed mode with the maximum pulse length of 1ms and repetition rate of 10Hz. The electronics of the ion source system, especially the power supplies, have good regulation, i.e., about 1V over 10kV. In typical operations, the discharge current is in the range of about 30-50A and the discharge voltage is about 200-250V. Forced air cooling is being used to control thermal load on the gas injection valve and on the cathode body. An improved cooling system will allow to increase the duty factor and eventually to run the source in cw mode.

Gas pressure plays a key role in determining the emission

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current density and the noise level of the beam. $H^-$ emission current density of more than $1A/cm^2$ has been achieved in an almost noiseless condition. A typical $H^-$ pulse is shown in Fig.1. Note that the noise on the beam pulse is close to its baseline value. Here, the $H^-$ emission current density

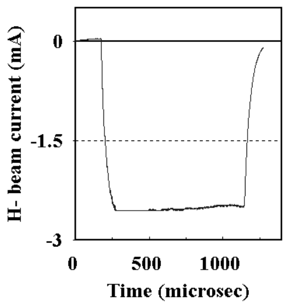


Fig. 1 Typical $H^-$ beam pulse from Penning SPS source with extraction aperture diameter $d_s$= 0.6mm.

is close to $1A/cm^2$. Figure 2 shows the dependence of $H^-$ current on extraction voltage for several values of discharge current over the range of 30-80A. These data represent the parameter space for the operation of the Penning SPS source.

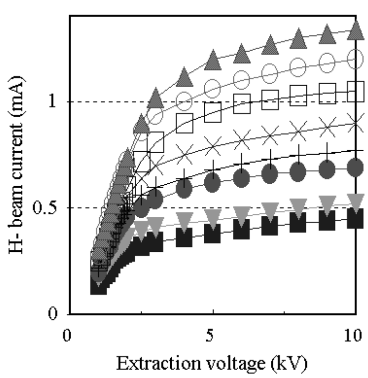


Fig. 2 $H^-$ beam current versus extraction voltage for discharge currents = 30A (■), 35A (▼), 40A (●), 45A (+), 50A (X), 60A (□), 70A (○), 80A (▲). These results correspond to the Penning SPS source with $d_s$= 0.6mm.

The beam brightness is a figure of merit of an ion source. The normalized beam brightness $B_n$ can be determined [14] from current density j and perpendicular temperature $T_\perp$ following the relation $B_n = mc^2j/(2\pi T_\perp)$. $T_\perp$ is obtained from emittance measurements. The emittance of the $H^-$ beam is measured using a pepper-pot system [15]. $T_\perp$ at the emission surface is estimated to be about 0.6eV for the situation in Fig.1, and the corresponding normalized brightness is about $2x10^{12}$ $A/(m\text{-}rad)^2$. These results represent the overall nature of the beam; the core beam is expected to exhibit much improved characteristics.

A retarding potential analyzer has been used to measure the energy spread [16]. The minimum energy spread of $\lesssim$ 2.5eV has been measured for angular beam intensity $I_\Omega$ of about 40mA/sr. This value of the energy spread is close to the resolution limit of the analyzer. Note that the beam intensity is about three orders of magnitude higher than liquid metal ion sources [17] or gas-field ionization sources [18]. The energy spread is observed to increase with noise level on the $H^-$ beam.

## 3 MAGNETRON SOURCE RESULTS

A magnetron-type negative ion source is operated in pulsed mode. The nominal pulse width is 50μs, and the duty factor is usually $1.5x10^{-4}$. We keep the anode body of the ion source at 165C, cesium (Cs) boiler temperature at 160C, Cs valve temperature at 270C and Cs line temperature at 300C. The discharge current is around 20-40A, the discharge voltage is about 180V, and the extraction voltage is varied over 0-30kV. Experiments have been conducted for different sizes of the extraction aperture -- diameter = 0.5mm and 2.5mm.

Figure 3 shows a typical $H^-$ beam pulse for extraction aperture of diameter = 2.5mm. The $H^-$ current is about 19mA for average $H_2$ gas pressure in the chamber =1.8-2.2x$10^{-5}$Torr,

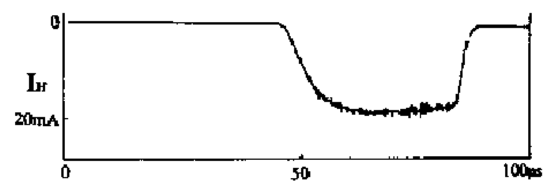


Fig. 3 Typical $H^-$ beam pulse for magnetron SPS source. Diameter of the extraction aperture $d_s$= 2.5 mm.

discharge current = 18A and extraction voltage = 30kV. This corresponds to an $H^-$ emission current density of $0.4A/cm^2$. Figure 4 shows typical beam pulse results for diameter of the extraction aperture = 0.5mm. The $H^-$ current is about 1.4mA, when the average $H_2$ gas pressure in the chamber = 1.0-1.5x$10^{-5}$Torr, discharge current = 25A, and extraction voltage = 20kV. This gives an $H^-$ emission current density of about $0.7A/cm^2$. The peak-to-peak noise level is about 0.15mA, which is about 5% of the total $H^-$ current. Higher beam current is obtained when the ion source runs at lower gas pressure. For an average pressure in the chamber at 0.8-1.2x$10^{-5}$ Torr, the $H^-$ current is about 2.3mA, when the discharge current = 30A and extraction voltage = 26kV. This yields an $H^-$ emission current density of about $1.15 A/cm^2$. The beam noise is less than 5% in this case.

The normalized emittance (90%) of the beam is measured in the small aperture case, and it is about 0.17mm-mrad. This yields a beam brightness (normalized) of about $8x10^9 A/(m\text{-}rad)^2$.

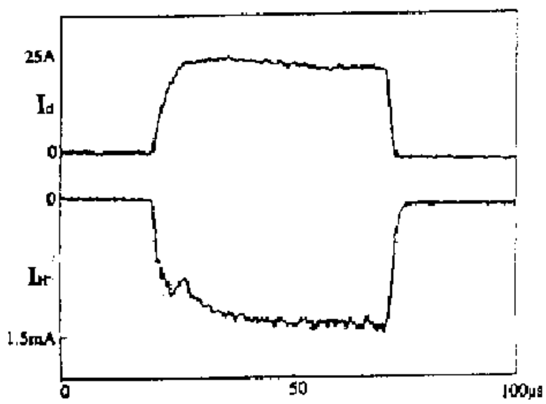


Fig. 4 Discharge current $I_d$ and $H^-$ beam current $I_{H^-}$ versus time for the magnetron SPS source. A smaller extraction aperture with diameter $d_s$= 0.5 mm is used here.

## 4 SCALING AND DISCUSSIONS

The results observed in the space-charge limited mode of operation of the two surface-plasma sources show the following behavior: (i) The $H^-$ beam current, $I_{H^-}$, increases almost proportionately with discharge current, $I_d$. (ii) $I_{H^-}$ increases with the aperture area and the extraction voltage. This trend of results suggests that the aperture of the Penning source can be increased from the current value of 0.6mm to about 2.4mm and that the source parameters can be appropriately scaled toward the requirements of a prototype high-current (~ 40mA), high duty factor (~ 10%) $H^-$ source suitable for pulsed spallation neutron source applications. It will be important to further extend our studies to critically examine the magnetron and Penning sources in higher duty-factor operations and test long-time reliability of the source and reproducibility of the beam characteristics. The excellent quality of $H^-$ beams with emission current density of $\sim 1 A/cm^2$ and the minimum energy spread of about $\lesssim$ 2.5eV from the Penning surface plasma source may open up avenues for many novel applications.

## 5 ACKNOWLEDGMENTS

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