HIGH BRIGHTNESS H^- SURFACE PLASMA SOURCES *

Vadim Dudnikov#, Rolland P. Johnson, *Muons, Inc., Batavia, IL USA;*

Abstract

Novel modifications of H^- source designs have been proposed. A new source under development is an advanced version of a Penning DT SPS (Dudnikov-Type Penning Surface Plasma Source) which will generate brighter beam in noiseless discharge, deliver up to 20 mA average current with better electrode cooling using new materials, and have longer lifetime, fast beam chopping capability, and reduced cesium loss.

INTRODUCTION

The problem of intense, high brightness negative ion beam production for accelerators and for neutral beam injection was solved in general by a small admixture of cesium vapor into a gas discharge ion source [1]. In subsequent experiments [2–5] it was demonstrated that cesium adsorption decreases the surface work function, enhances secondary emission of negative ions, and catalyzes the surface plasma generation of negative ions (SPG) caused by the interaction of the plasma with the electrode surface. Ion sources based on this process have been named surface-plasma negative ion sources (SPS). For SPS operation it is very important that the cesium admixture decreases significantly the current of co-extracted electrons. The high brightness SPS with Penning discharge was developed and described in [4]. During the last 30 years, proton accelerators with charge exchange injection have used some version of the compact SPS: cesiated magnetron SPS and cesiated Penning discharge SPS. For new accelerator projects it is necessary to develop negative ion sources with increased average current, increased brightness, and longer operation time.

COMPACT SPS

Magnetron (Planotron)

The cesiated magnetron (planotron) SPS was invented by Dudnikov in BINP, Novosibirsk and developed with Belchenko and Dimov up to 1 A of H^- current [5]. The magnetron design, used in FNAL, BNL, ANL, and DESY was developed and adapted by Chuck Schmidt. It has been operational in the Tevatron accelerator complex since 1978 [6]. The efficiency of H^- generation was improved significantly by cylindrical and spherical geometrical focusing [3]. The peak current of the H^- ion beam at the exit of the 750 keV_accelerator column is I_b ~70 mA with U_{ex} = 25 kV with a beam pulse length T= 0.075 msec at 15 Hz. A design of the magnetron with spherical focusing is shown in Fig. 1 (recently it was improved by machining a cylindrical groove around the entire cathode.). This design is optimized for low *df* operation with a low average discharge power P ~ 50 W.

#vadim@muonsinc.com

The optimum cathode temperature is T_c ~ 500ºC, and the anode temperature is T_a ~ 250ºC. For this reason, the cathode and anode are thermally insulated from the air-cooled base plate by macor machinable ceramic. The cathode is supported by insulators made of machinable ceramic macor with very low thermal conductivity (~0.01 W/cm-K) and with a weak contact between parts. The anode cover (plasma plate), which contains the emission aperture, is very thin and it is thermally insulated. The small cathode anode gap (~1 mm) is enough to hold the discharge voltage without short circuiting during long term operation. This design performs very well for production of up to 100 mA pulses with *df* up to 1%. In discharge without cesium, the discharge voltage is ~ 600 V and sputtering is very strong. With low voltage discharge (U_d ~100 V) and good cesium optimization, electrode sputtering caused by the discharge is very low. A more significant limitation of this CSPS lifetime is due to cathode sputtering caused by back accelerated positive ions, which stems from the use of a simple diode extraction system.

Nevertheless, this very compact and simple version of the magnetron has worked sufficiently well for high voltage pre-injectors and RFQs. With noisy discharge the efficient transverse ion temperature is relatively high ~10 eV. The normalized rms emittance with a 10 mm long slit is ~ 0.5 (π mm mrad). The magnetron has more than 80 years of accelerator operational experience. In all cases, magnetron sources are able to satisfy the requirements of the accelerators, and in most cases run at the space-charge limit for extraction.

All magnetron sources manage to provide beams for up to 9 months (up to 3.6×10^8 pulses ~ 2 A hrs) per year before requiring dismounting and cleaning. In the HERA Linac, a cesiated magnetron was tested for continuous operation for 32 months [7]. The duty factor can be increased by replacing the macor by AlN ceramic, which has much higher thermal conductivity.

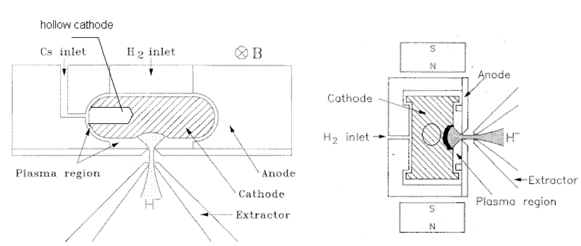

Fig. 1: Advanced version of magnetron with hollow cathode for suppression of discharge noise.

The magnetron can be improved by suppressing discharge noise, which will increase beam brightness. One possibility for noise suppression is to use a hollow cathode as shown in Fig. 1. This technique has been used in semiplanotrons [3, 8].

Penning Discharge SPS

The Penning SPS (shown in Fig. 2) uses a discharge with an anode window capped with cathodes at each end, along the magnetic field. Extraction of the ions is through a slit in the anode perpendicular to the magnetic field. The Penning discharge SPS was invented by Dudnikov in BINP [4]. It has had a long history of development at LANL [9,10]. Now it is successfully used at ISIS RAL [11,12] and is under development for the Chinese SNS. The fundamental difference between the magnetron and Penning sources is that in the magnetron, H^- ions produced at the cathode are directly extracted, while in the Penning source, the cathode has no line of sight and so ions must undergo a charge-exchange process on atomic hydrogen to reach the emission aperture. Discharge noise can be eliminated in a cesiated Penning SPS by optimizing the magnetic field and gas density or using a small admixture of heavier gas (N_2 in [10]). In this regard, emittance measurements have shown the Penning SPS always has higher brightness than the magnetron (and other ion sources). The effective ion temperature can be as low as $T_i \sim 1$ eV.

The LANL 1X Penning and ISIS Penning have essentially the same discharge chamber dimensions as in the first version of the Dudnikov type SPS [4]. The RAL Penning source that is in use at the ISIS facility delivered 35 mA (discharge *df*~2.5 %, beam *df* ~1%) after 650 kV pre-acceleration for a period up to 50 days.

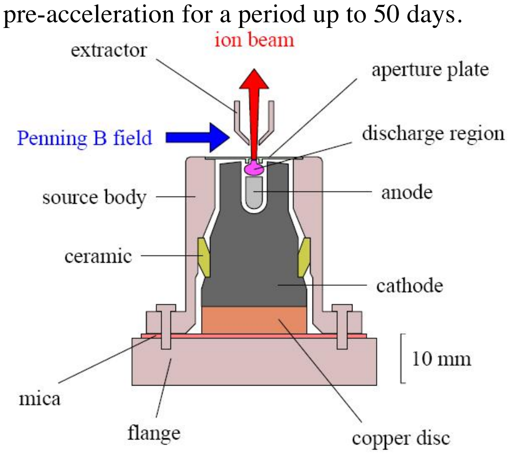

Figure 2: Schematic of ISIS version of Penning discharge SPS [11].

This version of SPS shown in Fig. 2 has limited cooling because the prototype was optimized for low *df* operation. The cathode cooling was improved by contact with a water cooled flange through a mica layer. But this layer has low thermal conductivity and limited heat transfer. The anode is cooled by air flow. However, the thin plasma plate that includes the emission slit has low thermal conductivity and is easily overheated. This ion source is currently under redevelopment at RAL for possible use on the European Spallation Source (ESS). The development goals are 70 mA H^- current with a short pulse of 1.2 ms at 50 Hz, and 70 mA H^- current with a long pulse of 2.5 ms for 50/3 Hz. The design emittance (rms, normalized) is < 0.3 (π mm-mrad) with lifetime greater than 20 days [12].

A Penning SPS for higher average current was built and tested at BINP by V. Dudnikov and co-authors [13]. Operation with beam current above 100 mA in 0.25 ms pulses with repetition rate of 100 Hz has been demonstrated for >300 hours (*df* = 2.5%). Operation with repetition rate of up to 400 Hz (*df* 10%) has been tested. Distinctive features of this Penning SPS compared with the ISIS source are its slightly larger discharge cell and more massive anode cover (plasma plate) with forced air or water cooling. The cathode has a strong pressed contact with a copper cooler. It is cooled by strong flow of water. A fast (0.1 ms) gas valve is used to inject gas at a repetition rate up to 500 Hz. Stable support of noiseless discharge has been established which is important for high brightness beam production.

At LANL, sources were designed and constructed applying plasma scaling laws and increasing two of the source dimensions by a factor 4 (the 4X source). This reduced the cathode power load from 16.7 to 2.24 kW/cm^2 while increasing the H^- current from 160 mA (0.5x10 mm^2 slit) to 250 mA (2.8x10 mm^2 slit) [8,9]. The measured rms normalized emittance is 0.15 π mm-mrad in the narrow slit dimension (2.8 mm). Emittance in the long slit dimension (10 mm) is 0.29 π mm mrad for an un-optimized slit extraction system at 29 keV extraction energy. It is possible that the last emittance increase, which affects only a small part of the beam, is connected with end effects of the slit. In this case, it can be improved by collimation.

Advanced Penning Discharge SPS

The schematic of proposed modification is shown in Figure 3. The design and operation of the proposed source are clear from the captions to Figs. 3 and 4.

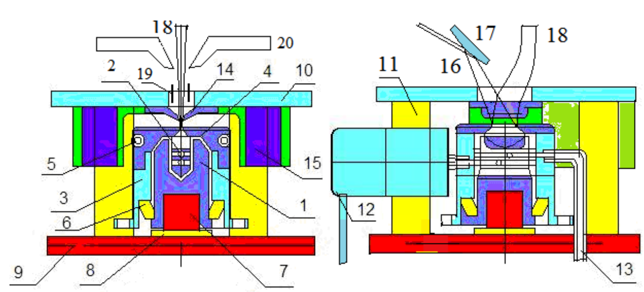

Fig. 3: Schematic of the Advanced version of the Penning discharge SPS for pulsed and CW chopped H^- beam production.

1- cathode; 2-anode; 3-source body; 4-cooled plasma plate5-anode cooling; 6- cathode insulator; 7-cathode cooler8- thermal conductive insulator (AlN); 9-cooled flange; 10- base plate; 11-high voltage insulator; 12- gas delivery system(pulsed valve); 13- cesium delivery system;14- extractor; 15- magnet (SmCo) + coils; 16- laser beam; 17-mirror; 18-negative ion beam; 19-suppressor/deflector; 20-accelerating electrode.

In discharges with high plasma density and increased distance between cathode surfaces (1) and emission aperture, the H⁻ ions from the cathode can't reach the emission slit without destruction. In this case mainly the surface plasma generation of H⁻ on the plasma electrode (anode SPG) around the emission aperture is important. In previous experiments it has been demonstrated that this anode SPG is efficient. The cesium admixture decreases the work function of the cathode and anode, to increase the secondary emission of electrons and negative ions. For stability of the optimal cesium film it is important to maintain the optimal surface temperature, which is easier for larger sources. The cesium concentration and conditions for SPG should be optimized on the plasma plate surface around the emission aperture. A more detailed drawing of the extraction/post- acceleration system is shown in Fig. 4.

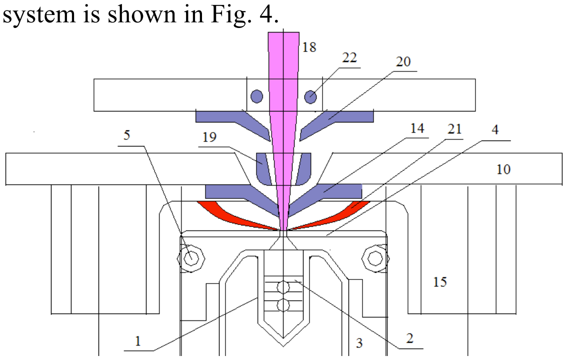

Figure 4:.Extraction system of DT SPS

1- cathode; 2-anode; 3-source body; 4- cooled plasma plate; 5-anode cooling; 14- extractor; 15- magnet; 18-negative ion beam; 19-suppressor/deflector; 20-acceleration electrode; 21-electron flux; 22-reflector.

Slit extraction is very adequate for H⁻ production by an anode SPG. Low ion temperature is preserved very well during slit extraction. The increased emittance along the slit, observed in work [11], is due to aberrations that affect a small fraction of the beam extracted from the ends of the slit and can be decreased by collimation.

A three or four electrode extraction system will be optimized to produce beam optics with minimum aberrations and low co-extracted electron current. The electron flux (21) is collected along magnetic field lines to the electron dump. It is important to suppress the secondary emission of H⁻ and cesium ions from the extractor. Suppression electrode (19) is used for collection of slow positive ions to prevent their acceleration into the discharge chamber which is important for suppression of electrode sputtering by these positive ions. Positive ions in the acceleration gap should be defocused by the electric field and collected. The reflector (22) is used to reflect positive ions generated in the H⁻ beam.

All these comments are applicable to the DC Penning SPS in publication [14]. The combination of proposed improvements can deliver high quality H⁻ beam with a pulse intensity ~100 mA and with average current up to 20 mA.

With a narrow slit emission aperture and narrow beam it is possible to have a fast and flexible deflection of the ion beam necessary for ion beam distribution. For beam deflection of a narrow beam it is possible to use relatively short deflector plates (19 in Fig.4) or a short travelling wave deflector with relatively low voltage for very fast (nanosecond) beam deflecting as in fast oscilloscopes. Fast beam chopping by such an extractor was tested in [15] to create 150 ns notches. Slower (~50 ns) beam manipulation connected with space charge neutralization was also performed.

With a smaller beam size (~3-5 mm) it is possible to have chopping with t~3-5 ns rise time with relative low deflection voltage, which is important for reliable long term operation. Deflecting plate designs and deflecting electronics from fast oscilloscopes can be used for this application. H⁻ beam focusing by a special electrostatic lens was demonstrated successfully for H⁻ beams with current up to 15 mA [14]. With this focusing, the rise and fall time of the chopped beam will be independent of space charge neutralization.

Cesium atom excitation by a resonant laser beam (16) will be used for effective suppression of cesium loss from the discharge chamber as disclosed in [16].

REFERENCES

[1] V. Dudnikov, "The Method of Negative Ion Production", SU Author Certificate, C1.H01 3/04, No. 411542, 10 March,1972, http://www.fips.ru/cdfi/reestr_rupat.htm; patent number 411542.

[2] V. Dudnikov, "Surface-Plasma Method of Negative Ion Production", Doctor Thesis, INP, Novosibirsk, 1977.

[3] V. Dudnikov, Rev. Sci. Instrum. 63(4), 2660 (1992); Rev. Sci. Instrum. 73(2), 992 (2002).

[4] V. Dudnikov, Proc. 4th All-Union Conf. On Charged Part. Accel., Moscow, 1974, V.1, p.323; English Translation, LASL. LA-TR-75-4, 1975; www.brookhaventech.com/pdf/dtpsps1.pdf.

[5] Yu. I. Belchenko, G. I. Dimov, and V. G. Dudnikov, BNL 50727, 79 (1977).

[6] Charles W. Schmidt, Linac 1990 (LA-12004-C), 259 (1990).

[7] J.Peters, Rev. Sci. Instrum., 71(2), 1069 (2000); APS Conf. 1097, pp. 236 (2008).

[8] Zhang Hua Shun, Ion Sources, Springer, 1999.

[9] P. Allison, "Experiments with Dudnikov-type H⁻ ion source", IEE Trans. Nucl. Sci., NS-24, 3, 1594 (1977) Rev. Sci. Instrum., 58 (2), 235 (1987).

[10] H. V. Smith et al, Rev. Sci. Instrum., v. 65 (1), pp. 123 (1994).

[11] R. Sidlow, et al. EPAC 96, 1996, THP084L.

[12] J. Thomason, et al. Rev. Sci. Instrum., 75 (5), 1735 (2004), Rev. Sci. Instrum., 75 (5), 1738 (2004). 20th ICFA Advanced Beam Dynamics Workshop, April 8 - 12, 2002. Dan Faircloth, et al, Rev. Sci. Instrum., **81**, 02A721 (2010).

[13] G. Dimov, G. Derevyankin, V. Dudnikov, IEE Trans. Nucl. Sci., V NS - 24, n.3, 1545 (1977).

[14] Belchenko et al. APS Conf. 1097, pp. 214-222. (2008).

[15] D. P. Moehs, AIP Conf. Proc. CP925, pp. 361-365 (2007).

[16] A. Dudnikov et al, Rev. Sci. Instrum., **81**, 02A714 (2010).