Fermilab FERMILAB-Pub-01/288 October 2001

30 Years of surface plasma sources for efficient negative ion production

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Thirty years ago, July 1, 1971, significant enhancement of negative ion emission from a gas discharge following a small admixture of cesium was observed for the first time. This observation became the basis for the development of the Surface Plasma Source (SPS) for efficient production of negative ions. In the SPS, negative ions are produced from the interaction of plasma particles with electrodes on which adsorbed cesium reduces the surface work function. Following this discovery, the emission current density of negative ions increased rapidly from j ~ 0.01 A/cm^2 to 3.7 A/cm^2 with a flat cathode and up to 8 A/cm^2 with optimized geometrical focusing in a long pulse SPS and up to 1 A/cm^2 for a DC SPS. Discovery of charge-exchange cooling decrease a negative ion temperature below 1 eV and increase the negative ion brightness by many orders to a level compatible with the best proton sources, $B = j/T > 1$ A/cm^2 eV. The intensity of negative ion beams was increased from mA to tens of Amperes. In this paper, features of different SPS s, negative ion beam formation, transportation, space-charge neutralization- over neutralization and instability damping are considered and practical aspects of SPS operation and high brightness beam production are discussed.

I. INTRODUCTION

One practical result of development of high brightness negative ion source is accepting of the charge-exchange injection in circular accelerators for a routine operation. Today, negative ion sources are the *Source of life* for gigantic accelerator complexes such as FNAL, BNL, DESY, KEK... The efficient and reliable operation of negative ion sources is largely responsible for the productivity of these facilities. Many discoveries in high-energy physics were made as a direct result of using the SPS negative ion source. The rapid development of high brightness H^- sources was stimulated by the first success of high current proton beam accumulation using charge-exchange injection [1]. Research in this area was supported by the interest in "Star Wars" [2]. In fact, these defense interests were also the main reason for the long delay of the first publication of results. Nonofficial communication, however, was relatively fast. Main early works in SPS development have been collected in report [3]. Before 1971, main attention was concentrated on development of the charge-exchange ion sources because there was no hope of extracting more than 10 mA of H^- directly from the plasma. On July 1, 1971, at the Institute of Nuclear Physic (INP), Novosibirsk, the author unexpectedly observed a very short duration enhancement of negative ion emission from a magnetron (planotron) plasma source following the introduction of a cesium admixture to the gas discharge.

Fortunately, this brief observation, considered in review [4], was not overlooked and was developed and understood as a new method of negative ion production that results from the interaction of a plasma with a surface. It became the basis for development of Surface Plasma Sources (SPS) [4, 5]. The original patent application [6] states "... a method of negative ion production in gas discharges, distinguished by adding to the discharge, along with a working substance, an admixture of substance with a low ionization potential such as cesium, to enhance the negative ion formation." Further development of the SPS was conducted in cooperation with Belchenko, Dimov (BDD) [7]. The theoretical bases of SPS operation were understood rapidly and enhancement of negative ion emission was explained [4, 5, 7]. The first high brightness SPS for use on an accelerator was developed by the author [8]. The Semiplanotron SPS with efficient geometrical focusing was developed by the author in 1977 [9]. Further R&D of high brightness SPS was conducted in cooperation with Derevyankin. Investigation and adaptation of SPS began very soon afterward in many laboratories in the U.S.A., Europe and Japan and International Symposiums for Production and Neutralization of Negative Ions and Beams were held [10]. Now, the Surface Plasma Method of negative ion production and SPS are discussed in many reviews and books (recently in book [11]). Good reviews of SPS for accelerators are presented in the reports of J. Peters [12-14]. The development of a high current SPS (tens of Amperes) for thermonuclear plasma heating is in progress and is now used in experiments [15]. Adaptation of a SPS for polarized negative ion production by charge - exchange with a slow negative ion has been developed in cooperation with A. Belov and INR team [16, 17]. This development has permitted use of charge exchange injection for accumulation of high intensity beams of polarized ions in circular accelerators [18].

Research and development of a heavy negative ion SPS for industrial application has had good success [19] but it is still necessary to further improve the DC SPS for heavy negative ion production to meet the broad requirements of many industrial applications.

II. FEATURES OF SPS

Many versions of the SPS have been developed and optimized for different applications. Cesium admixture enhances negative ion formation in all types of discharges, but the most efficient negative ion production and highest beam quality is attained using an SPS that is optimized for each application. Some basic discharge configurations of SPS are presented in Fig.1. Compact SPS (CSPS) such as magnetrons (planotrons) are seen in (*a*) and (*b*). A Penning discharge CSPS is shown in (*c*). A semiplanotron is shown in (*d*), and (e) is a hollow cathode SPS using a cold cathode glow discharge in a crossed E x B field. These CSPS have high plasma density, high emission current density of negative ions (up to 8 A/cm^2), small cathode – emitter gap (1-5 mm) (2) and small extraction aperture in the anode (1). They are very simple and effective, have a high brightness and high pulsed gas efficiency. CSPS's are very good for pulsed operation but electrode power density is often too high for DC operation. The opposite situation exists in the Large Volume SPS (LVSPS), presented in Fig.1, *f*, *g*, *h*, and first developed in Lawrence Berkeley Laboratory (LBL) [20]. The gap between emitter, 5, and extractor aperture is very large (8-12 cm) and the plasma and gas density must be kept low to prevent negative ion destruction. LVSPSs use a hot filament, 7, an RF coil, 9, or microwave discharge and multicusp magnets, 8, for plasma confinement. LVSPSs have a low power density and can be used for DC operation. Emission current density is only about 10 mA/ cm^2 and the brightness is not so high. Some versions of LVSPS with emitter (5) were adapted for heavy negative ion production [19]. LVSPS with production of negative ions on the plasma grid surface (anode production on Fig.1*g*) were adopted for high current (up to 40 A) negative ion beam production for plasma heating [15].

The efficiency of negative ion formation depends very much on the catalytic property of the surface, mainly the work function. For enhanced negative ion formation in the SPS, a mixture of substances with a low ionization energy, such as alkaline or alkaline earth elements or compounds, are used. Most efficient is the addition of cesium. Still, the surface work-function and catalytic properties of the surface for negative ion formation depends on many parameters including surface-cesium concentration, admixtures of other compounds, such as oxides, halides, nitrides, and surface temperature. Small changes in the surface condition dramatically change the efficiency of negative ion formation. It is a fine art and some magic to optimize the surface and plasma conditions for high efficiency negative ion formation. This is the main reason for the variation in efficiency of negative ion production even though conditions may look very similar.

Small changes in the surface condition can increase or decrease the intensity of a negative ion beam by large factors. Often, the intensity of H^- and D^- beams from a 1 x 10 mm emission slit as a function of discharge current I_d has been observed to vary from 200 mA to 10 mA for the same discharge current. A stronger variation can be seen in the beam brightness. The effective ion temperature can vary from a part of eV to several keV. It is relatively easy to obtain stable operation with low beam parameters such as current of ~ 30 - 50 mA, emission current density of ~ 0.5 - 1 A/cm^2 and transverse ion temperature, T_i ~ 5-10 eV. Present experience permits better optimization for long time stable production of high-brightness, high-intensity beams of negative ions (I ~ 0.1 - 0.15 A, B = J/Ti > 1 A/cm^2 eV, lifetime N > 10^8 - 10^9 pulses). The highest brightness can be reached only with noiseless operation. The level of discharge noise (hash) depends on many parameters. For stable discharge, the surface properties should be favorable for stable conditions and the frequency of electron scattering by plasma particles should be higher than the Larmour frequency. Discharge noise can be suppressed by a decrease of magnetic field and by an increase of the gas or Cs density. An admixture of heavy gas could be useful for noise suppression, but it increases sputtering.

The first versions of the SPS developed for charge-exchange injection of protons had an operating intensity I ~ 50 mA with pulse lengths of 0.05 to 1.0 ms, noisy discharges and a repetition rate up to 50 Hz [8,11-14,21]. H^- beam parameters of these SPS were sufficient for normal operation of large proton accelerator complexes for the past 25 years without significant modernization of ion sources. Now, new accelerator projects require an increase of the ion beam intensity and brightness. Some upgrading of existing SPSs could achieve the necessary increase of intensity, duty factor and beam quality without degradation of reliability and availability of the achieved satisfaction level.

The Fermilab Magnetron SPS has been operational since 1978 [21]. 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. Next Generation Accelerators need to have reliable operation with peak current after extraction (bending magnet) of I_b up to 0.15 A, pulse duration of T ~ 0.25 to 1ms, repetition rate F = 60 to 100 Hz and normalized emittance, $\varepsilon(90\%) = 1\ \pi$ mm mrad. An SPS with close parameters was tested with a relatively long run [22].

The lifetime of the SPS is determined by electrode sputtering and formation of flakes. It is dominated by cathode or anode sputtering caused by backward accelerated positive ions. Suppression of positive ions is important for increased lifetime. Optimized cesium film recycling (adsorption- desorption) can be used for shielding of electrodes from sputtering and can reduce the sputtering to a very low level. Cesium in the SPS acts like oil in an engine, increasing the operational lifetime. "Cold start" of the discharge without cesium for a few minutes is more destructive than many hours of low voltage operation. Emission current density of H^- up to J ~ 1 A/cm^2 has been observed in discharges without cesium but these discharges cannot be used for longtime operation. A fingerprint with a trace of Na or K could increase the efficiency of H^-

production significantly. But the power density in a discharge without cesium is very high and the sputtering rate is much higher. Electron emission from an ion source without cesium is very high. Recently, a new version of RF SPS has been developed in DESY [12-14]. An SPS with pulsed arc discharge was tested in Frankfurt University and in KEK for a high intensity Proton Driver.

III. LOW ENERGY BEAM TRANSPORT

The ion beam from a compact SPS has a very high current density (j ~ 1 to 3 A/cm^2) and perveance. For transport of these beams it is necessary to use a deep space-charge neutralization (compensation) or very strong continuous focusing by electrostatic forces as in the RFQ. Partial compensation of space charge with magnetic focusing and nosy operation will create a strong variation of focusing and lead to an increase of emittance by ellipse rotation. Still, this mode of transport is used in almost all injectors, and until recently it was acceptable. Space charge compensation by ions has some difference from the compensation by electrons. Ion oscillation in the potential of the beam is more coherent and can be the reason for very strong and fast beam-ion instability. Beam - ion instabilities have been observed recently in the electron beam of the Advanced Light Source (LBL) with increased residual gas density. In low energy negative ion beams, this instability was observed many years ago (1976). Development of this instability in H^- beam excite coherent oscillation of positive ions in the beam potential, excite quadrupole and dipole oscillations of the beam, develop a beam decompensation and emitteance growth.

To eliminate this problem, many versions of electrostatic focusing in the LEBT have been proposed. An ELEBT for SNS transport of an H^- beam of energy 65 keV with intensity up to 40 mA is now under development [23]. This beam-ion instability can be damped by over-neutralization of the beam to change the sign of the beam potential with an increase of the ion density in the beam. With increased ion and electron density, a stable beam transport can be achieved with additional focusing by reverse space charge. This solution can be used for transport over relatively short distances with acceptable levels of ion loss by stripping. A good solution is to use a short LEBT with a fast beam over-neutralization by streams of noiseless plasma from a separate plasma source

IV. ACKNOWLEDGMENTS

The author wishes to thank his colleagues Yu. Belchenko and G. Dimov who participated from the very beginning in the development of surface plasma method of negative ion production and SPS development. The creative contribution of the excellent technician P. Zhuravlev was very important for the successful development of the SPS. The author also wishes to thank G. Derevyankin, V. Klenov and M. Troshkov for their creative work in the development of high brightness SPS for accelerators. In addition, the author expresses gratitude to many teams in different countries, leaded by J. Alessi, C.W. Schmidt, J. Peters, P. Allison, V. Smith, J. Sherman, K. Ehlers, K. N. Leung, K. Prelec, Th. Sluyters, S. Guhary, G. Alton, J. Whealton, W. Stirling, Y. Mori , J. Ishikawa et al. for the adaptation of SPS in diverse real applications and for development of new versions of SPS. It was a pleasure to cooperate with A. Belov in adaptation of SPS for efficient production of nuclear polarized negative ions. It is pleasure to see an active development of new SPS for the new challenger applications.

Work supported by the U.S. Department of Energy under contract No.DE-AC02-76CH03000

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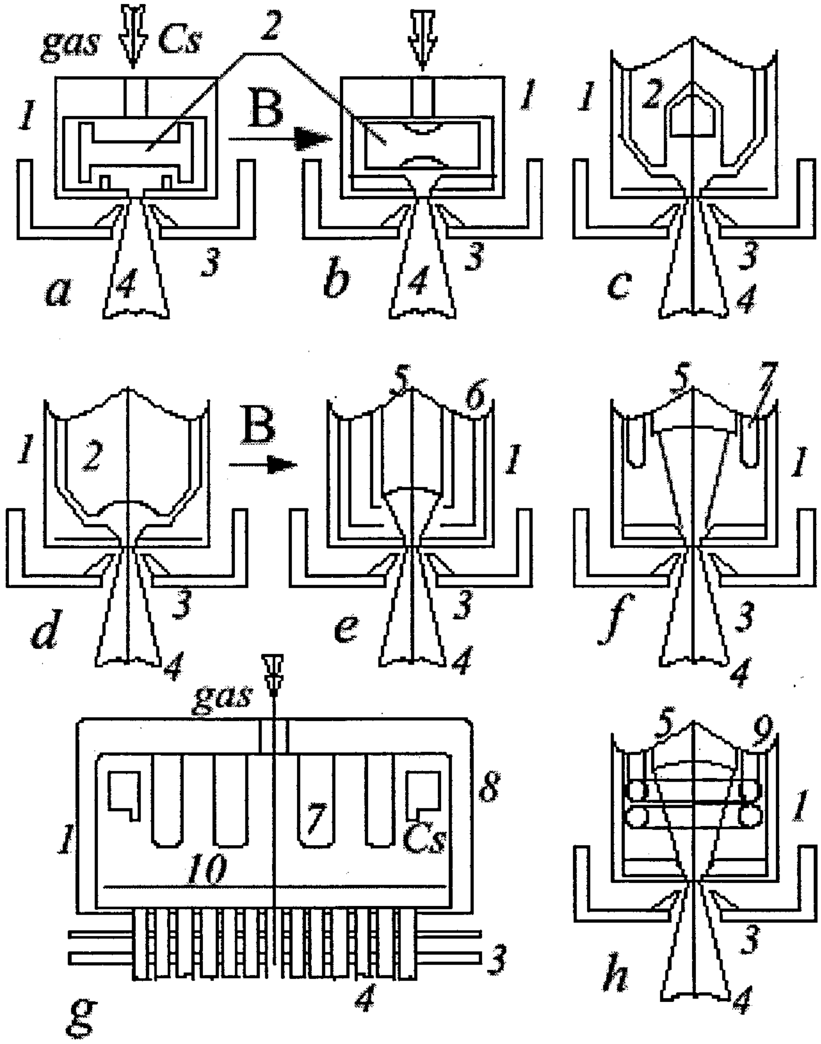
FIG.1. Schematic diagram of the basic versions of SPS: (a) planotron (magnetron) flat cathode; (b) planotron (magnetron) geometrical focusing (cylindrical and spherical); (c) Penning discharge SPS (Dudnikov type SPS); (d) semiplanotron; (e) hollow cathode discharge SPS with independent emitter; (f) large volume SPS with filament discharge and biased emitter; (g) large volume SPS with anode negative ion production; (h) large volume SPS with RF plasma production and emitter. 1- anode(gas discharge chamber); 2- cold cathode-emitter; 3- extractor with magnetic system; 4- ion beam; 5- biased emitter; 6- hollow cathode; 7-filaments; 8- multicasp magnetic wall; 9- RF coil; 10- magnetic filter.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