

CESIATION IN SURFACE PLASMA SOURCES

V. Dudnikov[#] and R. P. Johnson, Muons, Inc., 552 N. Batavia ave., Batavia, IL 60150, USA.

Abstract

Cesiation effect, a significant enhancement of negative ion emission from a gas discharge with decrease of co-extracted electron current below negative ion current was observed for the first time on July 1, 1971 by location into discharge a compound with one milligram of cesium [1]. This observation became the basis for the development of Surface Plasma Sources (SPS) for highly efficient production of negative ions from the interaction of plasma particles with electrodes on which adsorbed cesium reduced the surface work-function [2-5]. The emission current density of negative ions was increased rapidly from $j \sim 0.01 \text{ A/cm}^2$ to 3.7 A/cm^2 with a flat cathode and up to 8 A/cm^2 with an optimized geometrical focusing in the long pulse SPS, and up to 1 A/cm^2 in direct current (DC) SPS. Discovery of charge-exchange cooling helped to increase the negative ion brightness by many orders to a level comparable with the best proton sources, $B=j/T > 1 \text{ A/cm}^2 \text{ eV}$. Intensity of negative ion beams was increased by cesiation up to 10^4 times from mA to tens of Amperes. Now cesiation is routinely used in SPS for negative ions injection into accelerators and into large fusion devices.

INTRODUCTION

One practical result of development of high brightness negative ion source with cesiation is accepting of the charge-exchange injection in circular accelerators for a routine operation [6, 7]. Now SPS are "Sources of life" for gigantic accelerators complexes as SNS, FNAL, LANSE, BNL, ISIS, DESY, KEK, and an efficiency and reliability of these sources operation are determined a productivity of these big collaborations. Many results of the high energy physics were discovered with using of negative ion sources. Development of high brightness H⁻ sources was stimulated by first success of high current proton beam accumulation with using a charge-exchange injection [8] and supported by interest of "Star War" [9]. A recent circumstance was the reason of difficulties and long delay of first publications, but nonofficial communication was relative fast. Until 1971 a main attention was concentrated on the charge-exchange ion sources, because there was no hope to extract from the plasma directly more than 5 mA of H⁻. At July 1, 1971 at the Institute of Nuclear Physic (INP), Novosibirsk, significant enhancement of negative ion emission from the magnetron (planotron) plasma source followed by introducing a small cesium admixture to the gas discharge was observed by the author [1].

This observation, considered in review [4], was further developed and understood as a principle new method of negative ion production in interaction of plasma with a surface and a basis for development of a Surface Plasma

Sources (SPS). In the patent application [1] it was stated: "a method of negative ion production in gas discharges, comprising adding to the discharge an admixture of substance with a low ionization potential such as cesium, for example, for enhance a negative ion formation". Further development of SPS was conducted by cooperation Belchenko, Dimov, Dudnikov (BDD) [2]. The first high brightness SPS for accelerator has been developed by author [10]. The Semiplanatron SPS with an efficient geometrical focusing has been developed by author at 1977 [11]. Further R&D of high brightness SPS was conducted in cooperation with Derevyankin. Very fast development and adaptation of SPS has been start in many USA laboratories, in Europe and in Japan, and International Symposiums for Production and Neutralization of Negative Ions and Beams has been established [12]. Now the Surface Plasma Method of negative ion production and SPS are considered in many books (see for example book [13]). Good reviews of SPS for accelerators were presented in reports of Peters [14]. Development of high current SPS (tens of Amperes) for thermonuclear plasma heating is in progress and used in large Tokamaks and Stellarators [15]. Production of polarized negative ions by charge-exchange with a slow negative ion in SPS has been proposed by author and has been realized with a good success [16].

In R&D of heavy negative ion SPS for technology application a good success has been reached [17] 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. DC SPS for long time operation with accelerators has been developed [18]. Cesiated SPS with RF discharges for accelerators [19, 20] and for Neutral Beam Injectors (NBI) [21, 22] were improved recently significantly.

FEATURES OF SPS

Many versions of the SPS have been developed and optimized for different applications [2-5, 13-22]. 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 desired application. Some basic discharge configurations of compact SPS are presented in Fig. 1.

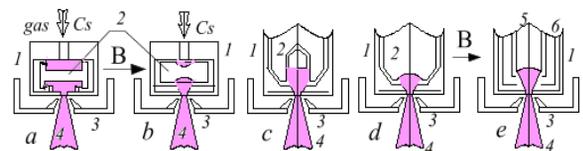


Figure 1: Schematic diagrams of the basic versions of CSPS.

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[#]vadim@muonsinc.com

Main components of SPS are: 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-multi-cusp magnetic wall; 9-rf coil; 10-magnetic filter. Compact SPS (CSPS) such as magnetrons (planotrons) are shown 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 $E \times B$ field. These CSPS have high plasma density, high emission current density of negative ions (up to 8 A/cm^2), small (1–5 mm) gap between cathode emitter (2) and a small extraction aperture in the anode (1). They are very simple and have a high gas efficiency with using of pulsed valve [23]. CSPSs are very good for pulsed operation but electrode power density is often too high for dc operation. However, CSPAs were successfully adopted for DC operation with the emission current density $\sim 300 \text{ mA/cm}^2$ [18].

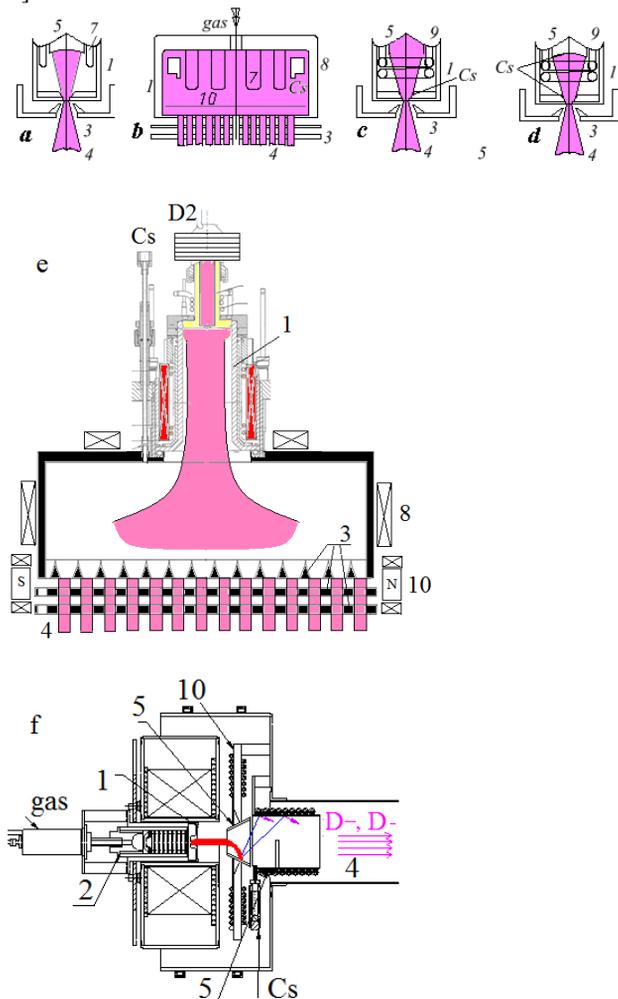


Figure 2: Schematic diagram of the basic versions of LV SPS.

The opposite situation exists in the large volume SPS (LV SPS) with discharge volume up to hundred litres, presented in Fig. 2(a-f). The first LV SPS (a) was developed in the Lawrence Berkeley Laboratory (LBL)

[24]. The gap between the 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. LV SPSs use hot filaments (7), RF coils (9), or microwave discharge and multicusp magnets (8) for plasma confinement. LV SPSs have a low power density and can be used for dc operation. Emission current density is only about 20 mA/cm^2 and the brightness is not so high. LV SPSs with production of negative ions on the plasma grid surface (anode production) on Fig. 2(b) were adopted for high current (up to 40 A) negative ion beam production for plasma heating by NBI [15]. LV SPSs for accelerators with RF discharges generating by solenoidal internal antenna is shown in Fig. 2 (c) [19]. Some versions of LV SPS (d) with emitter (5) were adapted for heavy negative ion production [17]. LV SPSs for NBI with RF discharges generating by solenoidal external antenna or by saddle antenna with longitudinal magnetic field are shown in Fig. 2 (e) [21, 22]. Version (f) is used in polarized H^-/D^- sources [16].

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, an admixture of substances with 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 depend on many parameters, including surface-cesium concentration, and admixtures of other compounds, such as oxides, halides, nitrides, and surface temperature [2-5, 22]. Example of the H^- beam current evolution during cesiation in the LV SPS with RF discharge driving by saddle antenna is shown in Fig. 3 [20].

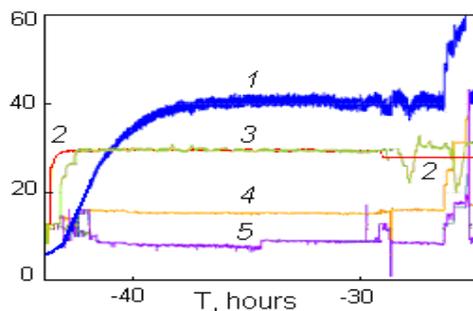


Figure 3: Evolution of H^- beam intensity of the saddle antenna RF LV SPS; 1- ion beam current; 2-gas flow; 3-collar temperature; 4-forwarded RF power; 5-reflected RF power.

After starting the rf discharge with rf power $P_{rf} = 24 \text{ kW}$, 10 Hz, 0.3–0.4 ms at magnetic field $B = 250 \text{ G}$, the initial beam current into Faraday cup $I_{fc} = 8 \text{ mA}$ grows to 42 mA during four hours without cracking the cesium ampoule as shown by curve 1 in Fig. 3. At the same time, the extracted current (which includes electrons and back-accelerated positive ions in addition to the H^- ions measured by the Faraday cup) decreased significantly.

The initial current density $J \sim 20$ mA/cm² generating with cleaned collar can be interpreted as volume generation but increase of J up to 100 mA/cm² with the same rf power must be interpreted as produced by surface plasma generation (SPG) through the electrode activation by the accumulation of impurities with low ionization potential (ILIP) substances on the collar ionization surface. H⁻ beam current $I_{fc} = 67$ mA was collected with RF power of 57 kW. This perfect “activation” was produced (without additional Cs) by the collection and trapping of traces of cesium compound remnants from SPS surfaces. Long conditioning is necessary because cesium is only slowly recovered from remnants. This slow accumulation demonstrates that the lifetime of these activating impurities on the collar can be very long. Nanograms of impurities are enough for enhancement of secondary emission of negative ions from the collar surface. Small changes in the surface condition can 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.

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 favourable for stable conditions and the frequency of electron scattering by plasma particles should be higher than the Larmor frequency. Discharge noise can be suppressed by a decrease of magnetic field and by an increase of the gas or Cs density [2-5]. 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 $I \sim 50$ mA with pulse lengths of 0.05–1.0 ms, noisy discharges and a repetition rate up to 50 Hz. H⁻ beam parameters of these SPSs were sufficient for normal operation of large proton accelerator complexes for the past 30 years without significant modernization of ion sources [25, 26]. 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 [19, 20, 27]. Further design and operation optimization of the SPS will improve the source efficiency, average current and lifetime. Cesium control and diagnostics will be improved with using of spectroscopy and lasers [28, 29]. The selfcesiation by recovery from remain impurities is considered in [20, 30].

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