PROGRESS IN THE NEGATIVE ION SOURCES DEVELOPMENT

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Abstract

Recent progress in development of advanced negative ion sources was connected with optimization of cesiation in surface plasma sources (SPS). The cesiation effect, a significant enhancement of negative ion emission from gas discharges with decrease of co-extracted electron current below negative ion current, was observed for the first time in 1971 by placing into the discharge a compound with one milligram of cesium. Subsequent developments of SPS for highly efficient negative ion production caused by the interaction of plasma particles with electrodes on which the adsorbed cesium reduced the surface work-function are described. In the last 40 years, the intensity of negative ion beams has increased by cesiation up to 10^4 times from three milliamp to tens of Amperes.

INTRODUCTION

One practical result of the development of high brightness surface plasma negative ion sources with cesiation (SPS) [1-4] is the wide use of charge-exchange injection in circular accelerators for routine operation[5,6]. Now SPS are "working horses" for large accelerator complexes at ORNL (SNS Spallation Neutron Source, Oak Ridge National Laboratory), FNAL (Fermi National Accelerator Laboratory), LANSCE (Los Alamos Neutron Science Center), BNL (Brookhaven National Laboratory), RAL (ISIS proton synchrotron at the Rutherford Appleton Laboratory), DESY (Deutsches Elektronen-Synchrotron), KEK/J-PARC (Japan Proton Accelerator Research Complex), and other accelerators.

The efficiency and operational reliability of these sources have determined the productivity of these laboratories and their big machines. Many results of high energy physics were discovered using negative ion sources. The development of high brightness H^- sources was first stimulated by successful high current proton beam accumulation using charge-exchange injection [4] and further supported by the interest in particle beam weapons as part of the "Star Wars"[3,4] program. The testing of H^- beam acceleration and neutralization in space (The Beam Experiment Aboard Rocket (BEAR)) considered in [3]. Military uses and classified work caused long delays of first publications, but nonofficial communication was relatively fast. Until 1971, the main attention was concentrated on charge-exchange ion sources because there was no hope to extract more than 5 mA of H^- directly from plasma.

The 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 in 1971 by placing into the discharge a compound with one milligram of cesium at the Institute of Nuclear Physics (INP), Novosibirsk, Russia [1].

This observation, considered in review [4], was further developed and understood as on principle new surface plasma method of negative ion production. In the patent application [1] it was stated: "a method of negative ion production in gas discharges, comprising adding into the discharge an admixture of substance with a low ionization potential such as cesium, for example, for enhancement of negative ion formation".

In subsequent experiments it was demonstrated that cesium adsorption decreases the surface work function from 4-5 eV to ~1.5 eV, which enhances secondary emission of negative ions caused by the interaction of the plasma with the electrode surface and thereby enhances surface plasma generation (SPG) of negative ions. Ion sources based on this process have been named Surface-Plasma Sources (SPS). The theoretical explanation of this enhancement of negative ion emission by cesiation was presented by Kishinevsky [4]. A small admixture of cesium or other impurity with low ionization potential (ILIP) in the gas discharge significantly improves H^- production. When done correctly, a cesiated SPS works very well [1-4] . However, improper cesiation can complicate ion source operation. For example, injection of too much cesium can cause the discharge to become unstable and sparking occurs in the extractor with loss of stable ion source operation. With low cesium concentration the efficiency of negative ion production is too low. With "proper" cesiation the efficiency of negative ion production is high and extended ion source operation is stable.

Further development of SPS was conducted by collaboration of Belchenko, Dimov, and Dudnikov . The development of the first high brightness SPS for accelerators was presented in[4]. The Semiplanatron SPS with efficient geometrical focusing has been developed by the author [3]. The development and adaptation of SPS started soon after in many USA laboratories, in Europe, and in Japan. A very active program of SPS development was established in BNL by Sluyters and Prelec. BNL Symposiums for Production and Neutralization of Negative Ions and the European Workshops on Production and application of Light Negative Ions Beams were established. Physical principles of SPS operation were presented in [2-4] and were reproduced in many reviews and books. Good reviews of SPS for accelerators were presented in reports of Peters. The development of high brightness SPS by Allison's group in LANL is considered in[3]. The development of high current SPS (tens of Amperes) for thermonuclear plasma heating was conducted by teams at LBNL and in Japan which is still in progress and is used in large tokamaks and stellarators[4]. Production of polarized negative ions by

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charge-exchange with a slow negative ions in SPS has been proposed by the author and has been successfully realized in colaboration with Belov [4].

Heavy negative ion SPS for technology applications has been successful[4], but it is still necessary to improve the DC SPS for heavy negative ion production to meet the broad requirements of many industrial applications. A DC SPS for long term operation with accelerators has been developed by a BINP team[4]. Cesiated SPS with RF discharges for accelerators and for Neutral Beam Injectors (NBI) were significantly improved recently by the SNS ion source group and by the IPP (Max-Planck-Institut für Plasmaphysik) team.

FEATURES OF SPS

Many versions of SPS have been developed and optimized for different applications[2-4]. Cesium admixtures enhance 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 a desired application. Some basic discharge configurations of compact SPS (CSPS) are presented in Fig. 1.

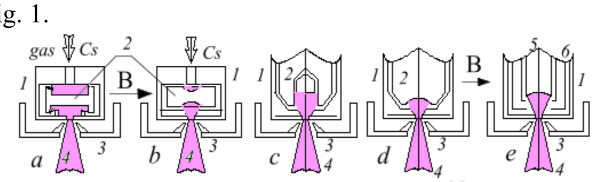

Figure 1:: Schematic diagrams of the basic versions of CSPS.: a) plain magnetron (planotron); b) magnetrons with focusing; c) Penning discharge SPS; d) semiplanotrons; e) hollow cathode SPS

Fig. 1 shows: a) plain magnetron (planotron); b) magnetrons with geometrical focusing; c) Penning discharge SPS (Dudnikov type source) was adopted for injection into ISIS; d) semiplanotron; e) hollow cathode SPS. The 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. The CSPS shown in Fig. 1 use a cold cathode glow discharge in a crossed *E*x*B* field. These CSPS have high plasma density (up to 10^{14} cm^{-3}), 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, have high energy efficiency (up to 100 mA/kW of discharge) and have a high gas efficiency (up to 30%) using pulsed valves. CSPSs are very good for pulsed operation but electrode power density is often too high for dc operation. However, CSPS were successfully adopted for DC operation with emission current density ~300 mA/cm^2 in and up to 1 A/cm^2 .A different situation is typical for the large volume SPS (LV SPS) with discharge volume up to hundred of liters, presented in Fig. 2. The first LV SPS (*a*) was developed at the Lawrence Berkeley National Laboratory (LBNL). 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. In the LV SPS, hot filaments (7), RF coils (9), or microwave discharge and multicusp magnets (8) are used for plasma generation at low gas density.

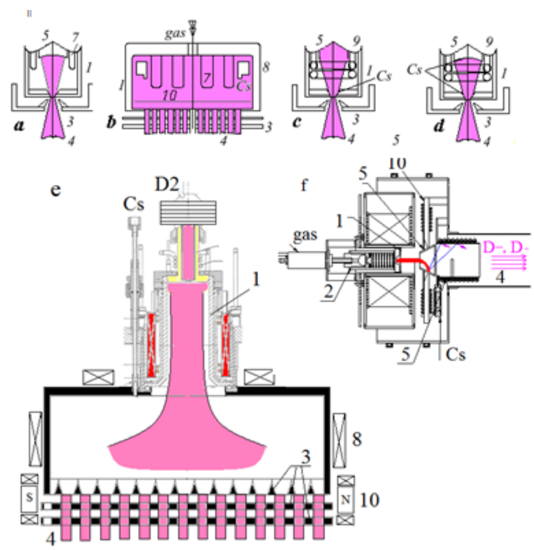

Figure 2: Schematic diagram of the basic versions of LV SPS.

LV SPS have a low power density and can be used for dc operation. Emission current density is below 100 mA/cm^2 and the brightness is not so high. LV SPS 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. LV SPS for accelerators with RF discharges generated by solenoid internal antennae is shown in Fig. 2 (c). Some versions of LV SPS (d) with emitter (5) were adapted for heavy negative ion production. LV SPS for NBI with RF discharges generated by solenoid external antennae or by saddle antennae with longitudinal magnetic field are shown in Fig. 2 (e). Version (f) is used in polarized H^-/D^- sources.

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 SPS, an admixture of substances with low ionization energy, such as alkaline or alkaline earth elements or compounds are used. The 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 the surface temperature Cesiation of the first SPS used discharge heating of pellets pressed from a mixture of cesium chromate with titanium powder placed into the discharge chamber[1-3]. The next SPS generation used independently heated ovens with the similar pellets [2-4] and ovens with metallic cesium. The discharge heating of cartridges with cesiun

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chromate become usable again in the RF SPS for SNS. Stable long term SPS operation can be established with very different cesium consumption parameters: from milligrams per week to grams per day. Sometimes cesiation from impurities remaining from previous operations can be enough for long term operation.

An example of the H^- beam current evolution during "self-cesiation" in a LV SPS with RF discharge driven by a saddle antenna is shown in Fig. 3 c, e.

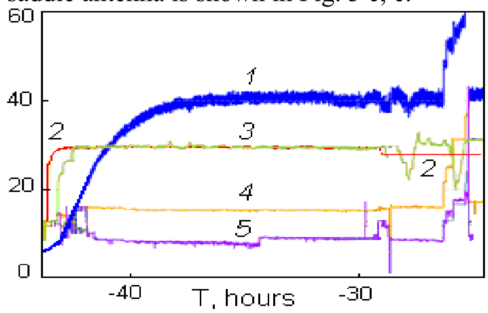

Figure 3: Evolution of H^- beam intensity of the saddle antenna RF LV SPS; 1- ion beam current; 2-gas flow; 3-collar temperature; 4-forward RF power; 5-reflected RF power.

In this LV SPS, H^- ions are produced by cesiation enhanced secondary emission from the surface around the emission aperture. Molecules of cesium containing impurities are dissociated and ionized in the discharge. The plasma has a positive ambipolar potential relative to the plasma electrode and positive Cs ions are transported to the plasma electrode by the electric field and accumulate on the surface around the emission aperture enhancing the H^- ion formation. The saddle antenna produces a higher plasma density on the axis of the discharge chamber and increases the efficiency of H^- generation.

After starting the RF discharge with RF power Prf = 24 kW, 10 Hz, 0.4 ms at magnetic field B = 250 G, the initial beam current into the Faraday cup Ifc= 8 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~ 20 mA/cm^2 generating with a cleaned collar can be interpreted as volume generation but the increase of J up to 100 mA/cm^2 with the same RF power must be interpreted as produced by surface plasma generation (SPG) through electrode activation by the accumulation of impurities with low ionization potential (ILIP) substances on the collar ionization surface. An H^- beam current Ifc=67 mA was collected with RF power of 56 kW.

SUMMARY

Cesiation is accepted as indispensable for high intense high brightness negative ion beam production.

SPSs with cesiation are "sources of life" and "work horses" in almost all high intense proton accelerators.Operation of these accelerators were not limited or compromised by SPS operation during last 30 years. For new project as SNS were developed new SPS with a DF 6% at pulsed current ~50 mA and lifetime ~1000 hours (integrated beam lifetime IBLT up to 2.7 Ahours). Cs consumption was reduced up to ~1 mg per week. Intensity of PD SPS was increased up to 60 mA at 5% DF. However, for internal and external cyclotron injection are used Cesium-less hot cathode discharge NIS with low energy and gas efficiency. In high energy heavy ion tandem implanters are used charge exchange NIS with Mg targets. Efficiency of Semiplanotron SPS was increased to ~100 mA/kW, similar to best proton sources. Intensity of H^-/D^- beams for NBI were increased to >40 A at emission current density up to 30 mA/cm2 and electron current less than H^- current. Used for regular operation in LHD and JT-60. Acceleration up to 1 MeV under development. DC H^- beams from PD SPS was increased to 25 mA with emission current density J~100 mA/cm^2. Push button operation is developed. Improve reliability and availability of SPS, lower ownership cost and push button operation are main task of negative ion sources development now.

Improving intensity of B^- (B_2^-) beam above 1-2 mA is important for semiconductor applications.

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