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HIGH BRIGHTNESS NEGATIVE ION SOURCES WITH HIGH EMISSION CURRENT DENSITY.

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Abstract. Through the development of Charge Exchange Injection [1] and Surface Plasma Sources (SPS) with Cesium Catalysis [2,3,4,5] the possibility for the accumulation of a high brightness proton beam in circular accelerators was increased greatly, and now it is more than sufficient for all real applications. The combination of the SPS with charge-exchange injection improved large accelerators operation and has permitted beam accumulation up to space-charge limit and **overcome** this limit several times [6]. The early SPS for accelerators have been in operation without modification for ~25 years. In this note an attention is concentrated on the seldom-discussed distinctive features of high brightness beam formation in noiseless regimes of negative ion source operation. Beam quality enhancement up to the level j/T>1 A/cm^{2}eV is possible by optimization of negative ion generation, extraction, and transportation in SPS with cesium catalysis. Advanced version of the SPS for accelerators will be described. Features of negative ion beam formation, transportation, space-charge neutralization- overneutralization, and instability damping will be considered. Practical aspects of SPS operation and high brightness beam production will be discussed.

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. Now negative ion sources are "Sources of life" for gigantic accelerators complexes as FNAL, BNL, KEK, DESY,.. 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 [1]. Until 1971 a main attention was concentrated on the charge-exchange ion sources, because was no hope to extract from the plasma directly more than 5 mA of H^-. After first observation of a strong increasing of negative ion production following a small admixture of Cesium into the gas discharges [2-4], and development of a first SPS for accelerators [5] has been start very fast development and adaptation of SPS in many USA laboratories, in Europe and in Japan, and International Symposiums for Production and Neutralization of Negative Ions and Beams has been established [7]. Now the Surface Plasma Method of negative ion production and SPS considered in many books (recently in book [8]). Good review of SPS for accelerators presented in reports of J. Peters [9-11]. Production of polarized negative ions by charge- exchange with a slow negative ion in SPS has been proposed and has been realized with a good success [12]. This development has permeate to use a charge exchange injection for accumulation of high intense beams of polarized ions in circular accelerators [13].

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) [14]. 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 [15]. 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 [16].

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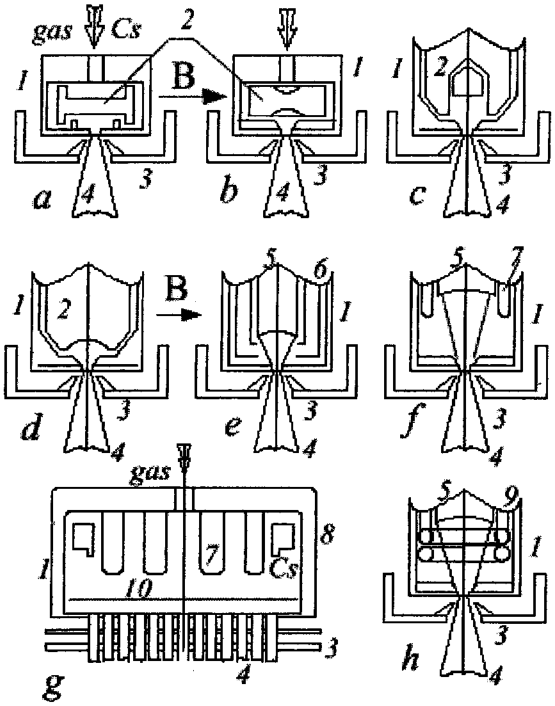

FIGURE.1. Schematic diagram of the basic versions of SPS: (a) planotron (magnetron) flat cathode; (b) planotron (magnetron) geometrical focusing (cylindrical and spherical); (c) Penning discharge SPS (Dudnikov type SPS); (d) semiplanotron; (e) hollow cathode discharge SPS with independent emitter; (f) 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.

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 very much on many parameters such as 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 condition for high efficiency of negative ion formation. This condition is a strong reason for the variation in efficiency of negative ion production although conditions look very similar. Small changes in the surface condition can increase or decrease the intensity of a negative ion beam by large factors. The intensity of H^- beams can has a variation up to 10 times for the same discharge current. A stronger variation can has a beam brightness. An efficient ion temperature can has a variations from a part of eV to some keV.

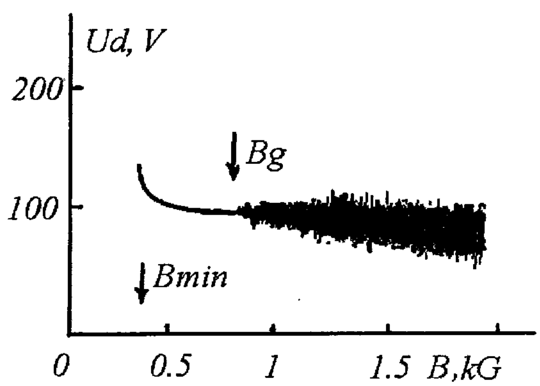

FIGURE 2. The discharge voltage and level of noise vs. magnetic field in SPS with Penning geometry.

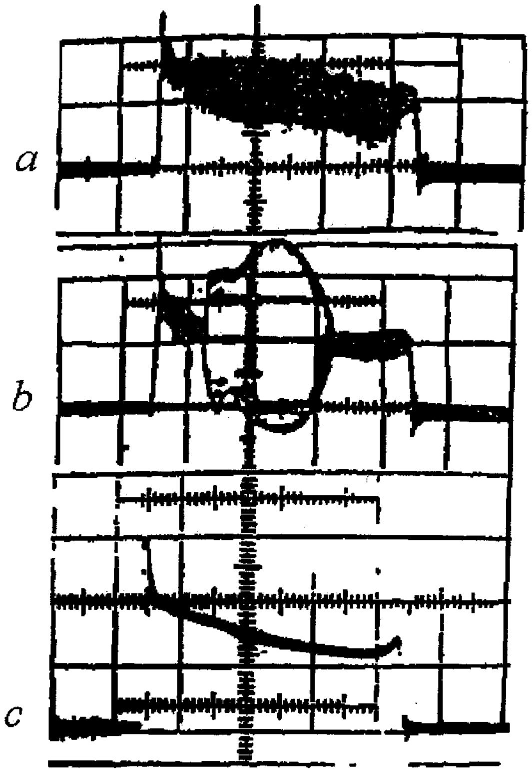

FIGURE 3. The examples of discharge voltages for different conditions in SPS. (*a*) a discharge with noise; (*b*) a discharge with RF generation: (*c*) noiseless discharge.
Vertical scale is 100 V/div; Horizontal scale is 0.2 ms/div.

It is easier to have stable operation with relatively low beam parameters such as intensity I ~30-50 mA, emission current density J ~0.5-1 A/cm^2, transverse ion temperature Ti ~5-10 eV. Present experience permits better optimization for longtime 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). Highest brightness could be realised only with noiseless operation. The level of discharge noise (hash) is depend of many parameters. For stable discharge a surface properties should be in the stable conditions and frequency of electron scattering by plasma particles should be higher than Larmor frequency. A discharge noise could be suppressed by decrease of magnetic field as shown in Fig. 2 and by increase a gas or Cs density. Admixture of heavy gas could be useful for noise suppression, but it increase a sputtering. Examples of discharge voltages with a different level of noise are shown in Fig. 3. A transition from the noise discharge (*a*) to noiseless one (*c*) increases a beam brightness at order of magnitude.

NEGATIVE ION SOURCES FOR ACELERATORS

The first versions of the Surface-Plasma Sources (SPS) developed for charge-exchange injection of protons have an operating intensity I ~50 mA with pulse lengths of 0.05-1 msec, noisy discharges and a repetition rate up to 50 Hz [6-11]. H^- beam parameters of these SPS was sufficient for normal operation of large proton accelerator complexes during the past 25 years without significant modernization of ion sources. Now, new accelerator projects need an increase of the ion beam intensity and brightness. Some upgrading of existing SPS 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 [17]. The peak current of the H^- ion beam at the exit of the 750 keV_accelerator column is I_b=65 mA with an extraction voltage Uex= 20 kV, and I_b ~70 mA with Uex = 25 kV with a beam pulse length T= 0.075 msec at 15 Hz. The pulse length could be increased with a new arc discharge pulser and adjusted parameters. It is useful for stable operation to have a discharge power supply as a current source with a high impedance (Z= 5-10 Ohm, now Z=1 Ohm) and corresponding higher voltage. After optimization of the discharge electrode configuration the intensity was increased above I_b= 0.1A without increasing the discharge power. Gas delivery optimization should allow a longer pulse and higher intensity without an increase of the gas loading.
An optimized extraction system with a suppression electrode should improve the beam intensity, beam quality and beam space-charge neutralization with a low gas pressure. A suppression of a back accelerating of the positive ion should suppress cathode and anode sputtering by accelerated positive ions - a main reason for the shorting of ion source lifetime. Improved cathode and anode cooling is necessary for increased discharge pulse length and intensity. The

Semiplanatron version of the SPS is the best one for operation at higher duty factor.
From previous experience it is possible to have reliable operation of a SPS with parameters: peak current after bending magnet I_b ~0.12-0.15 A with pulse duration of T ~0.25 msec, repetition rate F=100 Hz normalized emittance $\varepsilon(90\%)$ =1π mm mrad. SPS with these parameters was tested with a relatively long run as 300hs [18].
Lifetime of SPS determined by electrode sputtering and flakes formation. It is dominate a cathode or anode sputtering by back accelerated positive ions.
Optimized cesium film recycling (deposition-desorbtion) could be used for shielding of electrodes from the sputtering and can reduce the sputtering to a very low level. Cesium in the SPS acts as an oil in an engine, increasing the operational lifetime. "Cold Start" of a discharge without cesium for a few minutes could be more destructive than many hours of low voltage operation. Electron emission from discharges without cesium is very high.
Recently, new version of RF SPS has been developed in DESY[9-11], SPS with pulsed arc discharge in Frankfurt University and in KEK for high intense Proton Driver.

LOW ENERGY BEAM TRANSPORT

The ion beam from a compact SPS has a very high current density (j~1-3 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.
A good solution could be a short LEBT with a fast beam over-neutralization by streams of noiseless plasma from a separate plasma source

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