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DESIGN FEATURES OF AN AXIAL-GEOMETRY, PLASMA-SPUTTER, HEAVY NEGATIVE ION SOURCE

G. D. Alton
Oak Ridge National Laboratory*
P. O. Box 2008
Oak Ridge, Tennessee 37831-6368

ABSTRACT

An axial-geometry, plasma-sputter, negative ion source, which utilizes multi-cusp, magnetic-field, plasma-confinement techniques, is under design at the Oak Ridge National Laboratory (ORNL). The source is based on the principles of operation used in a recently developed radial-geometry source which has demonstrated pulsed-mode peak intensity levels of several mA for a wide spectrum of heavy negative ion species. The pulsed-mode characteristics of the source are well suited for tandem electrostatic accelerator/synchrotron injection applications. Mechanical design features include provisions for fast interchange of sputter samples, ease of maintenance, direct cooling of the discharge chamber, and the use of easily replaced coaxial LaB_6 cathodes. Principal features of the source will be described and the results of computational studies of the ion extraction optics will be presented.

INTRODUCTION

Recent developments[1-4] have demonstrated the utility of a radial-geometry, plasma-sputter, negative ion source for producing high-intensity (several mA) pulsed beams of a wide spectrum of atomic and molecular negative ion species. This source type, as well, has shown promise for dc beam generation at mA-intensity levels.[5] The pulsed-mode performance characteristics of this source type are particularly well suited for use in conjunction with the tandem electrostatic accelerator when used as an injector for a heavy ion synchrotron, while the dc mode of operation is commensurate with stand-alone tandem accelerator operation. For the synchrotron heavy ion accelerator, high-intensity, pulsed beams of widths 50-300 μs at repetition rates of 1-50 Hz for a wide

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spectrum of atomic and molecular species are typically required. The feasibility of injecting mA beam intensities with these pulse characteristics into large tandem accelerators without deleterious effects has been recently demonstrated at the Brookhaven National Laboratory and at the University of Tsukuba.[4] The specific need for a high-brightness source for use in conjunction with the Holifield Heavy Ion Research Facility (HHIRF) 25URC tandem electrostatic accelerator at the Oak Ridge National Laboratory (ORNL), which would serve as an injector for the proposed Heavy Ion Storage Ring for Atomic Physics (HISTRAP),[6] was the primary motivating factor which led to the design of the source described in this report.

PRINCIPLES OF NEGATIVE ION FORMATION

The sputter technique has been utilized as a practical means for the generation of negative ion beams for a number of years. In such sources, positive ion beams, usually formed by either direct surface ionization of a Group IA element or in a heavy noble gas (Ar, Kr, or Xe) plasma discharge seeded with alkali metal vapor, are accelerated to energies between a few hundred eV and several keV where they sputter a sample containing the element of interest. The presence of a fractional layer of a highly electropositive adsorbate, such as cesium, on the surface is critically important for the enhancement of negative ion yields during the sputtering process.[7] A fraction of the sputter ejected particles leave the adsorbate covered surface as negative ions and are accelerated through an extraction aperture in the source. The present source, like the source described in Refs. 1-4, will use the plasma sputter technique in forming high-intensity beams (a few to several mA) of a wide spectrum of species.

SOURCE DESIGN FEATURES

The high-intensity, radial-geometry, plasma-sputter, negative ion source, described in Refs. 1-4, has proved to be a reliable, stably operating source with an extremely long lifetime for pulsed-mode operation, which can provide a wide spectrum of negative ion beams suitable for a variety of applications. The intensity levels obtained are often higher by factors of 30-100 than those which can be generated in cesium sputter-type sources such as described in Refs. 8-10 and yet the emittances of the source are comparable for pulsed-mode operation;[11] they also match the calculated acceptances of large tandem accelerators such as the 25URC tandem accelerator at ORNL,[12] and, in principle, ion beams from this source should be transportable through such devices. However, the radial-geometry source is not equipped with provisions for rapid sputter sample interchange such as required for use at a research facility which operates continuously and which must provide beams from a wide spectrum of species on user demand. The radial-geometry source, as well, was designed for exclusive use for generation of H^- beams for low-duty-factor synchrotron injection applications which require no direct cooling of the discharge chamber and is, thus, improperly cooled for the high power requirements necessary for dc-mode operation. The LaB_6 filaments used to initiate and sustain the discharge are not designed for fast interchange. When they break, either as a consequence of physical erosion or mechanical stress, an extensive period of time is required for replacement. The source shown in Fig. 1 was designed in an attempt to overcome some of these handicaps and to provide a source which could be used for both pulsed and dc modes of operation.

The operational characteristics of the axial-geometry source are expected to be identical in almost every detail to the radial-geometry source.[1-4] The source is constructed primarily of stainless steel and utilizes metal-to-ceramic bonded high-voltage insulators and low-voltage feedthroughs. Design emphasis has been placed on the ability to rapidly change the source itself and all degradable components. The cesium oven is mounted externally, permitting easy access for servicing, while providing good thermal isolation between the discharge chamber and the oven itself. The main source can be quickly and easily disassembled for cleaning and other maintenance operations. The source assembly is composed of four major independent assemblies: (1) the sputter probe vacuum airlock assembly; (2) a freon-cooled, stainless steel discharge chamber onto which is attached the cesium oven, discharge gas support system, coaxial geometry LaB_6 cathodes, and SmCo and AlNiCo plasma confinement magnets, (3) a ceramic-to-metal bonded alumina (Al_2O_3) insulator to which is attached the high-voltage extraction electrode system, and (4) the coaxial LaB_6 cathode assembly. The power supply arrangement required for operation of the source is shown in Fig. 2.

Sputter Probe Vacuum Airlock Assembly. The sputter probe assembly consists of a thin wall, 12.7-mm-diameter chromium plated copper tube to which is attached the 50-mm-diameter copper sample holder onto which is clamped the material of interest. The sample holder is cooled by continuous freon flow through a concentric tube arrangement. The probe can be inserted into and withdrawn from the source through the airlock valve which is sealed against atmospheric pressure by a conventional elastomer gasket. The vacuum interlock assembly is attached to an externally mounted ceramic-to-metal insulator which in turn is fastened to the back flange of the source. The insulator is used to isolate the probe-vacuum airlock assembly from the source body. Based on experience with sources equipped with similar provisions, the total time required for withdrawing, replacement, and reinsertion of the sputter probe sample material is expected to be the order of 10 minutes.

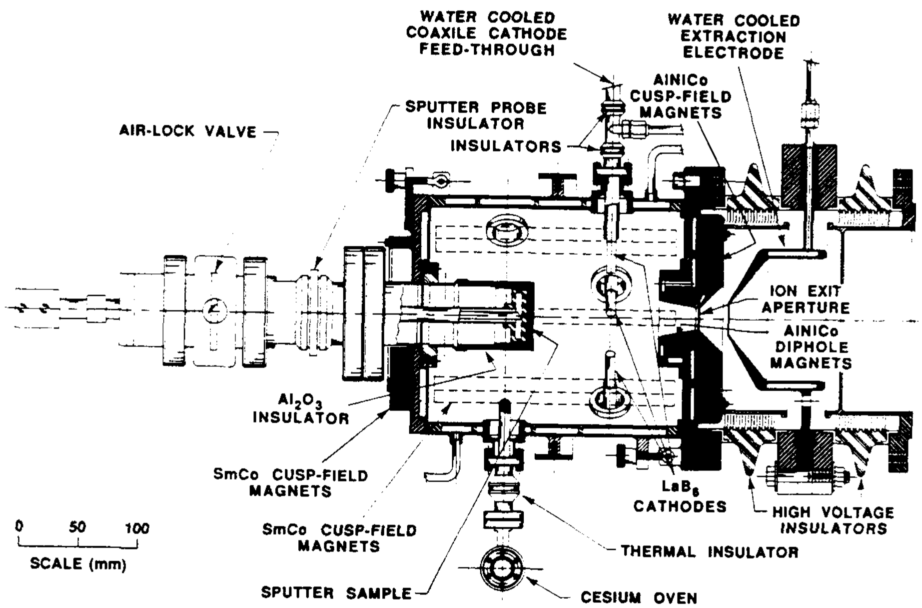

Fig. 1. Axial-geometry, plasma-sputter, negative ion source (top view).

The sputter probe/airlock assembly is insulated from the source housing with an insulator designed to withstand potentials up to ~-10 kV. When fully inserted into the discharge chamber, the sputter probe is surrounded by an Al_2O_3 insulating sleeve which prevents all internal negatively biased components other than the sample material from being bombarded by positive ions extracted from the surrounding plasma. Two geometries of sputter samples will be utilized. In cases where malleable metal sheet material containing the species of interest is readily available, samples 1-1.5 mm in thickness will be pressed by means of a die fixture into a 50-mm-diameter spherical sector probe with radius of curvature $\rho \simeq 210$ mm for focusing the negative ion beam generated in the sputtering process through the exit aperture of the source. Samples which are brittle must be formed from solid materials. Composite sintered compounds or mixtures of compounds will be typically 5 mm in thickness with a spherical radius of 210 mm machined into the face of the material. These samples will be indirectly cooled by clamping the sample to a spherical or flat geometry copper heat sink appropriately contoured to the respective sample geometry. The sputter probe assembly will be cooled by a freon heat exchange unit maintained at 15°C.

Vacuum Discharge Chamber and Plasma Confinement Arrangement. The vacuum/discharge chamber is made of stainless steel equipped with freon coolant passages to protect the five sets of equally spaced SmCo and ALNiCo plasma discharge confinement magnets from thermal degradation by the radiant power incident on the walls of the

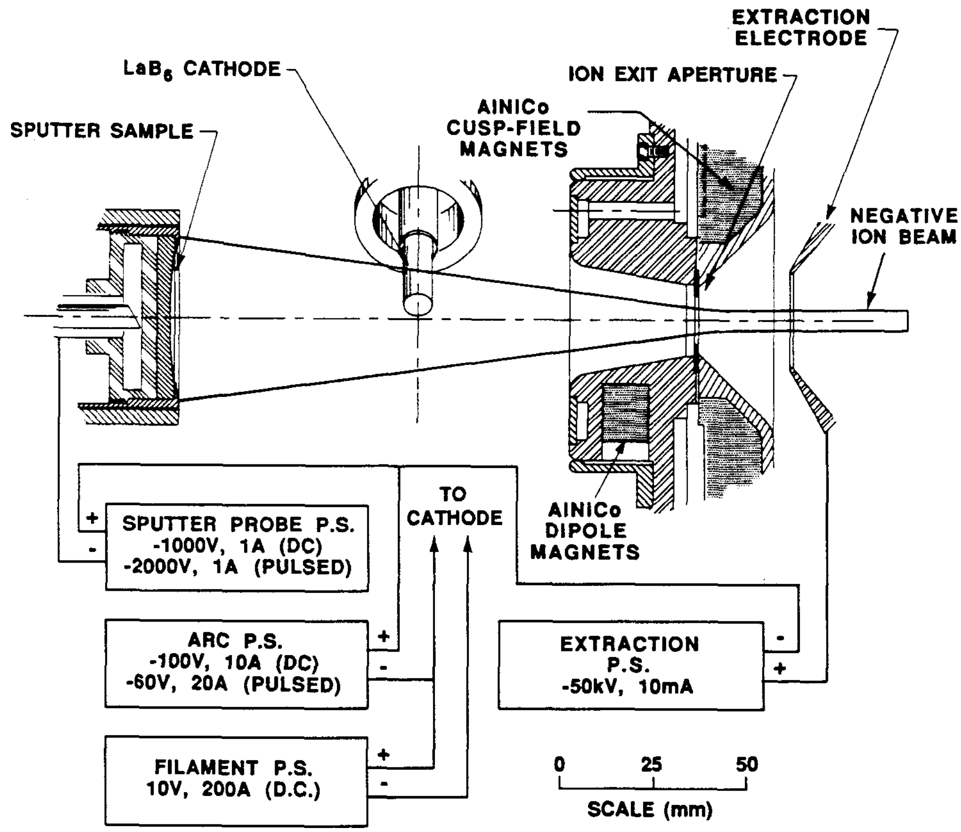

Fig. 2. Power supply arrangement for the axial-geometry, plasma-sputter, negative ion source.

chamber arising from the plasma discharge and high temperature LaB_6 cathodes. Plasma confinement is effected by the use of five rows of SmCo permanent magnets, equally spaced circumferentially around the diameter of the cylindrical chamber. The external and internal flanges of the chamber are equipped with five equally spaced, azimuthally oriented SmCo and AlNiCo magnets, respectively. The internal flange is equipped with a set of dipole AlNiCo magnets to inhibit electron extraction from the source and thereby reduce loading to the extraction power supply and a replaceable tantalum aperture. Initially, the exit aperture will be 10 mm. The chamber is attached to the rear and front flanges by means of thumb screws for ease in disassembly for cleaning and other maintenance operations.

<u>The Ion Extraction Electrode System and Extraction Optics</u>. One of the advantages of the plasma-type sputter negative ion source lies in the fact that, when operated in a high-density plasma mode, the negatively biased sputter probe containing the material of interest is uniformly sputtered. This characteristic makes it possible to take advantage of the large area spherical- geometry lens system which is formed between the

spherical sector sputter probe and the plasma sheath which conforms to the geometry of the probe. Negative ions created in the sputter process are accelerated and focused through the plasma to a common focal point, usually chosen as the ion exit aperture of the source, and then pass into the field region of the extraction electrode system. Within the plasma, the ion beam is free of space charge effects. Thus, the sputtered particle energy and angular distributions, and aberrations in the acceleration plasma lens system determine the beam size at the focal point of the spherical lens system. At high beam intensities, space charge effects come into play when the beam exits the plasma and enters the extraction region of the source. However, because the beam energy is 500-1000 eV upon exit from the plasma region of the source, space charge influences on the beam are reduced. After exiting the source, the beam is further accelerated by a two-stage electrode system insulated by high-quality Al_2O_3 insulators. Typically, the ion beam will be accelerated through a potential difference of 20 kV in the first stage and by an additional 30 kV in the second stage. The optics of the ion extraction aperture and second stage field regions are designed to provide inwardly directed radial restoring forces to the beam to offset, in part, space charge effects which will suddenly appear in the slow moving, intense heavy negative ion beams upon exit from the plasma region of the source.

The ion optics of the ion generation and extraction regions of the source equipped with two different extraction electrode systems have been studied computationally through use of the code described in Ref. 13. Examples of such calculations are shown in Figs. 3 and 4 which display ion trajectories for a 3.5-mA O^- or a 1-mA Au^- ion beam generated at the sputter probe surface and accelerated through the field-free region of the plasma and finally into the extraction lens system at energies up to 81 keV and 51 keV, respectively. The simulation results shown in Fig. 3 are for an extraction system used at LAMPF,[14] while the results shown in Fig. 4 represent the present electrode system. The optics of the latter electrode system are better suited for beam transport into the 25URC tandem electrostatic accelerator injector and, therefore, will be incorporated as the extraction electrode system for the axial-geometry subject source.

Coaxial LaB_6 Cathode Assembly. The source will utilize directly heated coaxial-geometry LaB_6 cathodes to initiate and sustain the plasma discharge. The cathode structure shown schematically in Fig. 5 is very similar to the design described by Leung et al. in Ref. 15. The high melting point, chemical inertness, low work function, and low sputter ratio properties make LaB_6 especially attractive for such applications. The coaxial geometry is desirable because it minimizes the magnetic field surrounding the cathode and thus permits emission and escape of low-energy electrons from the surface. More importantly, the design allows easy and fast interchange of cathodes through a single metal-to-metal vacuum seal feedthrough.

ION ENERGY: 81 keV; ION BEAM INTENSITY: O−: 3.5 mA; Au−: 1mA

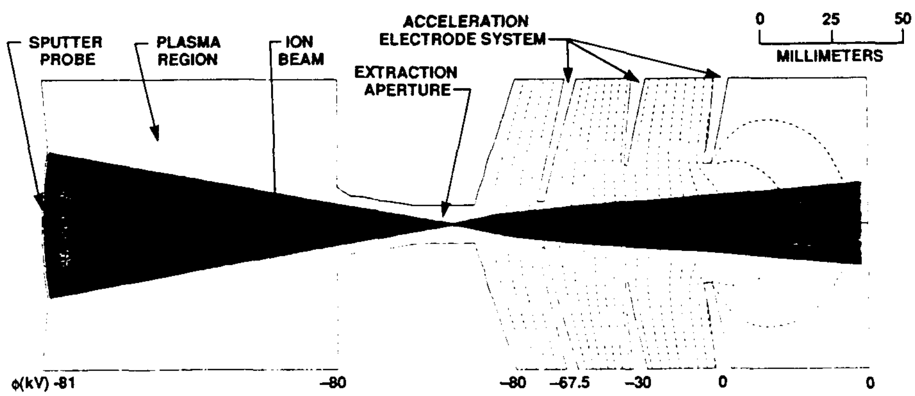

Fig. 3. Negative ion optics of the axial-geometry, sputter heavy negative ion source equipped with the extraction system used at LAMPF.[14]

ION ENERGY: 51 keV; ION BEAM INTENSITY: 0^-: 3.5mA; Au^-: 1mA

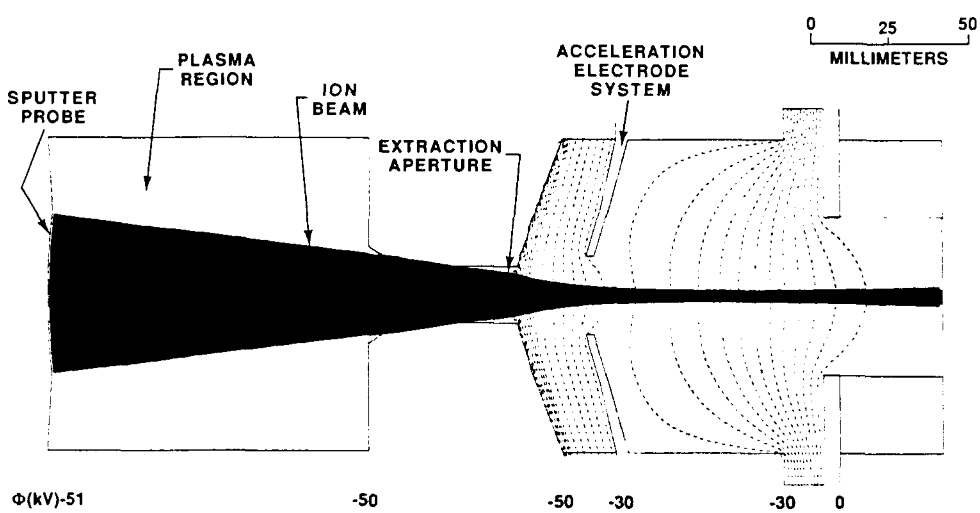

Fig. 4. Negative ion optics of the axial-geometry, sputter heavy negative ion source equipped with a two-stage extraction electrode system shown in Fig. 1.

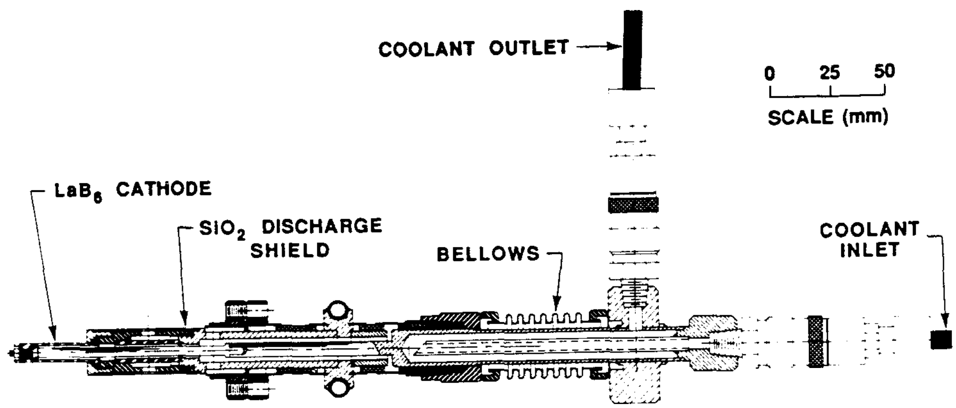

Fig. 5. Schematic representation of the coaxial-geometry LaB_6 cathode assembly.

The cathodes are machined from solid pieces of LaB_6 which have thin hollow cylindrical walls (6.4 mm diameter, 1 mm thick, and 25.4 mm in length). Each cathode assembly is 35 mm in length and has a 2-mm-thick top flange for attachment to the outer conductor and a 5-mm-thick bottom for attachment to the central tantalum conductor as shown in Fig. 5. Rhenium foil is used to provide good electrical contact between the LaB_6 cathode and the top molybedum nut and tantalum outer electrode, and between the bottom molybedum nut and central tantalum conductor.

EXPECTED PERFORMANCE CHARACTERISTICS

The operational parameters and intensity capabilities of the subject source are expected to be similar to those of the radial-geometry source and therefore, the reader is referred to Refs. 1-5 for specific information concerning the species and intensity capabilities, as well as the qualities (emittances), of beams produced in this type of source. The anticipated operational parameters for pulsed-mode operation of the source are shown in Table 1. For example, the source is expected to generate peak beam intensities close to those reported in Ref. 4 for the radial-geometry source, which includes a list of more than 20 negative ion species, including 6 mA C^-, 10 mA Cu^-; 8 mA Pt^-; and 10 mA Au^-. The emittances of beams extracted from the source are also expected to be close to those of the radial-geometry source (typically, 11-17 π mm.mrad $(MeV)^{1/2}$ at the 80% contour level, depending on the beam intensity).

Table 1. Expected pulsed-mode source operating parameters.

Arc current	15-20 A
Arc voltage	30-60 V
LaB_6 cathode current	130 A
LaB_6 cathode temperature	1450°C
Xe gas pressure	2.3 x 10^{-4} Torr
Sputter probe voltage	500 V
Beam extraction voltage	50 kV
Cesium oven temperature	190-205°C
Beam pulse width	1-5 Hz
Repetition rate	1-50 Hz

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