A RADIAL GEOMETRY CESIUM PLASMA SOURCE WITH IMPROVED MECHANICAL FEATURES*

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An improved version of the radial geometry cesium plasma negative ion source, described by Alton and Blazey, has been designed, evaluated and employed for use during routine operation of the Holifield Heavy Ion Research Facility (HHIRF) tandem accelerator. The mechanical features of the source have been improved to facilitate rapid change of degradable parts such as the sputter probe insulator and cathodes and to provide better thermal isolation of the externally mounted oven from the discharge chamber. The source has demonstrated improved operational stability, higher intensities and increased reliability over its predecessor. Negative ion beams from more than twenty-five elements have been provided for the HHIRF experimental program including several molecular hydride beams from difficult elements such as Be, Mg, Ti, Sc, Nd and Zr. A detailed description of the mechanical features of the source as well as the negative ion yield dependence on certain operational parameters are presented.

1. Introduction

The need for high-intensity negative ion sources with universal species capabilities and high-beam quality characteristics for tandem accelerator

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applications has led to the development of a variety of negative ion sources during the past few years. To a large extent, the rapid advancement of negative ion source technology is attributable to the discovery of the technique of enhancing secondary negative ion sputter yields by covering the sample surface containing the material of interest with minute amounts of Group IIA elements.^[1] Several sources predicated on the utilization of this discovery have been reported in the literature. (Recent reviews of this and other aspects of negative ion source technology may be found in references 2 and 3.)

The source described in this report, like its predecessor which was described by Alton and Blazey,^[4] embodies some of the principles associated with the radial geometry source developed by Andersen and Tykesson^[5] which was the prototype, in principle, for a generation of sources which operate in a cesium vapor environment. The development of Andersen and Tykesson led to sources with significantly improved performance in terms of intensity and emittance including the widely used axial geometry sources which rely exclusively on surface ionization to effect positive ion formation. (For details concerning axial geometry negative ion sources, the reader is referred to these proceedings and references 2 and 3.)

2. Principles of Operation

The principles of operation of the source have been described previously^[4] and therefore only a brief reiteration will be given here. The source, illustrated schematically in Fig. 1, can be described in terms of the traditional radial geometry nomenclature in that the negative ion beam is

extracted perpendicular to the direction of the plasma discharge. (Since the plasma column is usually circular in cross section, extraction of ions perpendicular to the direction of the discharge is customarily referred to as the radial direction.) A weak magnetic field (~ 150 G) produced by a lightweight permanent Al-Ni-Co magnet is used to collimate the primary electron beam which is thermionically emitted by a 1.5-mm diameter tantalum filament situated at the end of the ionization chamber. The geometry and plasma generation techniques are thus very similar to those usually associated with radial geometry Penning discharge positive ion sources. However, the plasma discharge power and the magnetic field flux density are much lower in this source. The electron beam produces an approximately uniform plasma by collisional impact with neutral cesium vapor introduced into the chamber from the oven. (This method differs from the Andersen-Tykesson source^[5] which relies principally on surface ionization of cesium in thermal contact with heated tantalum filaments situated near the sputter probe to produce the positive cesium ion beam.) Cesium vapor is introduced into the discharge chamber from an oven which has been designed for operation under conductance-limited flow conditions. Auxiliary discharge support gas (usually Ar) may be introduced into the chamber by means of a standard leak valve to supplement the cesium vapor in order to provide the minimum pressure necessary for stable discharge; chemically active gases may also be introduced into the chamber for generation of atomic negative ions from gas itself or for chemical combination with the sputter probe material in the formation of molecular

negative ions. The latter technique is particularly effective and often necessary for enhancing yields from low electron affinity materials.

The source is equipped with two filaments, mounted in modular filament holders at either end of the ionization chamber, only one of which is active during operation. This arrangement provides a means of doubling the source lifetime when filament breakage is the limiting lifetime factor. An air-lock is provided to facilitate quick change of the sputter probe and the internal boron nitride probe insulator.

The plasma, in an attempt to preserve its electrical neutrality, forms a thin sheath about the sputter probe, across which the negative and positive ions are accelerated. The sputter sample is cylindrical ($\phi = 10$ mm, typically) with a concave spherical negative ion emission surface machined into the face of the material. The radius of curvature of the spherical surface is 15 mm. The sputter probe, containing the material of interest is maintained at ~ -1000 V relative to the discharge chamber. Positive ions extracted from the plasma, generally under space-charge limited conditions, impact the probe and sputter material back through a thin layer of cesium adsorbed on the surface. Negative ions, produced in the sputter-surface ionization process, are focused by means of the plasma lens through an aperture situated at a distance equivalent to the radius of curvature of the spherical sputter probe. This provides a means of extraction with good ion optical properties from a relatively large sputter probe area.

3. Computational Analysis of the Negative Ion Generation Region of the Source

The radial geometry source relies on electron impact to produce a plasma from which positive ions are extracted and accelerated to energies of ~ 1000 eV for uniformly sputtering the spherical surface of a sample containing the material of interest. In the normal mode of operation, the sample is positioned away from the exit aperture by the radius of the spherical surface. For a uniformly distributed plasma surrounding a perfectly spherical ion emission surface and monoenergetic negative ion emission, the optics of this concept are aberrationless. However, as is well known, the emitted sputtered negative ions have a pseudo-gaussian energy distribution with most probable energy of ~ 10 eV. This energy distribution along with space charge effects and aberrational effects of the beam extraction and transport systems are the principal contributors to the finite emittance of the source.

Simulation studies of the negative ion generation and extraction regions of the source were made by self-consistent solutions to the Poisson-Vlasov equations for extraction of ions from a collisionless plasma. For negative ion extraction simulation in the present source, the plasma surrounding the probe and occupying the volume between the sputter probe surface and exit aperture was simulated by a Boltzmann energy-distribution model. Plasma space charge neutralization and sheath formation surrounding the negatively biased probe are automatically accounted for

during solution of the equations. A complete description of the numerical algorithms utilized in these computations is given in reference 6.

Examples of analyses of the extraction region of the source for two probe geometries are shown in Fig. 2. These figures display beam envelopes which are expected when the source is operated in the high-plasma density mode for two probe geometries with respective radii of $r = 15$ mm and $r = 23$ mm, both of which are positioned at 15 mm from the exit aperture. The emission current density assumed for both cathodes is $200 \mu\text{A}/\text{cm}^2$. The negative ions generated at the surface are accelerated to 1000 eV by the plasma sheath, traverse the plasma and exit the aperture into a post-acceleration field region where they achieve a final energy of ~ 21 keV. Because of differences in the sputter probe radii, the beams are focussed at different positions within the post-acceleration field and the resulting angular divergences are rather different. The solution for extraction from the probe with radius $r = 15$ mm produces a tightly focussed crossover at the exit of the aperture which results in a half-angle divergence of $\theta_{\text{rms}} = 2.33^\circ$ while extraction from the larger probe with radius $r = 23$ mm produces a much lower angular divergent beam of half angle $\theta_{\text{rms}} = 0.79^\circ$. Neither geometry is clearly superior. The probe with $r = 15$ mm radius permits the use of a smaller exit aperture which is commensurate with cesium conservation while the larger probe geometry ($r = 23$ mm) allows a greater spacing between the source and the first beam transport lens.

4. Mechanical Design

The source assembly is composed of three major independent assemblies: (1) a ceramic-to-metal bonded alumina (Al_2O_3) insulator to which is attached the reference potential extraction electrode system; (2) a freon-cooled housing into which the source itself is fitted; and (3) the source unit itself. (The housing also has machined recesses for attaching the Al-Ni-Co magnet.)

The source unit is comprised of a back flange to which is attached the plasma discharge chamber, electrical current feed throughs for the filaments, the gas feed nozzle assembly, the cesium oven assembly, and the sputter probe assembly. The unit is modular and can be quickly inserted or removed from the housing assembly by thumb screws in a matter of a few minutes. The plasma discharge chamber houses modular hot cathode (filament) assemblies located at each end of the discharge chamber, the ion exit aperture ($\phi = 1.5$ mm, typically), and the boron nitride probe insulator. The boron nitride insulator can be interchanged while the source is under argon through the vacuum airlock assembly. The probe assembly consists of a stainless steel tube, 12.7-mm in diameter, to which is attached the sample of interest. The sample 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. The tube vacuum seal is made by a conventional elastomer gasket. The vacuum airlock 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. The gas feed nozzle and oven nozzle assemblies are attached to the back flange by metal-to-metal vacuum flanges and are spring loaded against the discharge chamber by convoluted, high-spring tension bellows. The nozzle, plasma discharge chamber interfaces are designed to prevent gas or cesium leakage at the interface.

Extensive experience has been gained with the source during routine HHIRF tandem accelerator operation. The merits of the design have proven themselves through significant reduction of accelerator down time for source maintenance, source interchange, sample interchange and oven servicing. As examples, the following time periods are found to be typical of specific operations: (They do not, however, include source cool down time whenever this is necessary.)

Source unit interchange: < 10 minutes

Sample interchange: < 20 minutes

Boron nitride insulator interchange: < 25 minutes

Cesium oven servicing: < 25 minutes.

5. Source Lifetime

Extensive experience gained during routine operation of the HHIRF tandem accelerator indicates lifetimes per filament ($\phi = 1\frac{1}{2}$ mm) exceeding 200 hours with values ranging upward to 500 hours. Thus a total filament lifetime between 400 and 1000 hours is typically experienced. Generally,

the source is operated until both filaments have been expended at which time the source is interchanged with a previously outgassed standby source. Pre-outgassing of the source is found to reduce start-up time by as much as eight hours.

The time period between cleaning of the high-voltage insulator or downstream einzel lens, usually necessitated by excessive sparking attributable to accumulation of condensed cesium, typically exceeds 2500 hours of source operation. The long time period between servicing is to a large extent attributable to the design of the housing which provides a large directly cooled surface for condensation of cesium emitted through the source aperture and to performance of the cesium oven whose operation has been carefully characterized.

6. Source Operational Parameters

Information concerning yield dependence versus source operational parameters such as cesium oven temperature and sputter probe voltage is essential for optimum, efficient and stable source operation.

Characteristics of the Cesium Oven

Efficient negative ion generation is dependent on the deposition of approximately one monolayer of cesium on the surface being sputtered. Too little cesium will not minimize the work function while excess cesium may raise the work function to that of elemental cesium (~ 1.89 eV) and as well, hinder the sputtering and ejection of target material. Both effects are detrimental to the production of negative ions.

The cesium oven temperature determines the rate at which vapor flows into the ionization chamber and therefore the arrival rate of cesium onto the sputter probe sample surface. In the present source, the cesium oven is attached to the back flange of the source by means of metal to metal gasketed flanges. The nozzle which penetrates the source back flange, equipped with a conductance limiting flow tube, is spring-loaded against the source body. The interface between the source body is designed to prevent cesium vapor leakage at the point of contact. The oven heater is a commercially available, 175 watt (120 VAC), band type device that slips over the cylindrical body of the cesium reservoir. The oven is modular and positioned external to the main vacuum for easy access. During operation, the oven is wrapped with aluminum foil to provide radiation shielding and the temperature is monitored with a chromel-alumel thermocouple. The cesium oven temperature is adjusted by varying the oven heater current according to the heater-temperature relationship shown in Fig. 3. The oven incorporates the conductance limited flow design principles utilized in the previous radial geometry source^[4] — a design which provides excellent flow control and very effectively thermally decouples the oven from the plasma discharge chamber.

Negative Ion Yield Versus Cesium Oven Temperature

In order to operate the source under optimum yield conditions, the correlation between negative ion yield and cesium oven temperature and negative ion yield and sputter probe voltage must be known. Figure 4

displays total negative ion yields of Cu^- and Ni^- as a function of cesium oven temperature. The maxima in temperature for these elements are seen to both occur at $\sim 265^\circ\text{C}$.

Two processes occur on the increasing side of the curve which affect the yield. The sputter probe current increases due to an increase in flow rate of cesium with temperature which leads to an increase in the sputter probe current and hence the sputtering rate. The sputter probe current will continue to increase until space charge limited conditions set in for fixed probe voltage. Perhaps the most important effect is that the work function of the surface decreases as the cesium layer increases to its optimum value. However, the optimum surface layer may be quickly achieved. On the decreasing side of the curve, the effective cesium layer becomes greater than optimum and the work function probably increases to that of elemental cesium and at even higher oven temperatures, the increasing cesium flow rate begins to interfere with the ejection of target material from the surface.

Negative Ion Yield Versus Sputter Probe Voltage

The probe voltage affects the sputter rate and hence the negative ion yield, therefore the relationship between negative ion yield and sputter probe voltage is also very important. A sputtering voltage too low relative to optimum cesium flow rate conditions reduces the negative ion yield from the standpoint of the number of particles sputtered as well as greater interference between the sputtered target particles and the effective cesium layer. In contrast, a voltage which is too high can

detrimentally disturb the cesium layer by sputtering away the cesium monolayer too fast resulting in an increasing work function and a decrease in the negative ion yield. At some probe voltage and cesium oven temperature, the negative ion yield will reach the temperature limited condition and the yield will decrease with increasing sputter probe voltage. Evidence of these effects are shown in Fig. 5 which displays relative negative yield as a function of probe voltage for several negative ions. (The negative ion yield versus sputter probe voltage characteristics of this source are found to be identical to those of the initial source.^[4]) As noted, the value of the sputter probe voltage which corresponds to optimum negative ion yield varies from element to element.

7. Negative Ion Yield Data

The maximum negative ion yields extracted from the present source are close to those reported previously for similar sources. Table 1 presents a partial list of negative ion beams either obtained from this source or its predecessor.^[4] An interesting aspect of the source is its ability to produce beams of H^- and heavy element molecular hydrides which may be difficult to produce in useful intensities in other sources. Of particular interest for tandem accelerator applications are hydrides of the Group IIA elements.

The technique of employing alloys has been found useful in controlling sublimation and excessive chemical reaction rates during source operation for the more active Group IIA elements.^[7] Their use also has the attractive

advantage of providing other ion beams such as Cu^- from a single probe as well. This suggests the use of composite alloy probes for generating several different ion beams from the same probe, obviating the necessity of changing probes during specific accelerator runs. The chemical effects, if any, of the alloy constituent Cu on the negative ion yield are not known at this time. Interesting intermetallic alloy negative ion beams from all of the Group IIA elements have also been observed — a discovery which may have future implications for providing negative ion beams from other difficult elements.

8. Summary and Conclusions

An improved version of the radial geometry cesium plasma negative ion source, described by Alton and Blazey,^[4] has been designed, evaluated and employed for use during routine operation of the Holifield Heavy Ion Research Facility tandem accelerator. The source has been designed with improved mechanical features which facilitate rapid change of the source itself, as well as degradable components such as the sputter probe insulator, and which provide better thermal isolation between the discharge chamber and the cesium oven. Operational experience gained over a period of more than one year has demonstrated the merits of these design features and indicates that the source is a versatile, dependable, and prolific generator of a wide variety of negative ion beams with a long lifetime. The source has also demonstrated improved operational stability and higher beam intensity capabilities than its predecessor. Negative ion beams have

been provided for the HHIRF experimental program from more than twenty-five elements and thirty different isotopic species, including molecular hydride beams from difficult elements such as Be, Mg, Ca, Ti, Sc, Nd and Zr.

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Table 1

Negative ion yield data

Ion	Probe Material	Probe voltage (V)	Arc conditions voltage (V)	current (A)	Negative ion yield (μ A)	Support gas
H ⁻	Ni	80	175	1.1	176	Cs + H ₂
BeH ₃ ⁻	Be	1100	27	0.8	4	Cs + H ₂
BeO ⁻	Be	1200	50	0.75	25	Cs + O ₂
C ⁻	C	1500	65	1.0	20	Cs + H ₂
CN ⁻	C	1200	75	0.75	15	Cs + N ₂
O ⁻	CuO	1000	50	0.80	15	Cs + Ar
MgH ₃ ⁻	60% Mg - 40% Cu	1200	60	0.4	12	Cs + H ₂
AlH ⁻	Al	1000	75	0.6	2.3	Cs + H ₂
Si ⁻	Si	1200	17	0.80	10	Cs + Ar
P ⁻	GaP	1100	40	0.6	8	Cs + Ar
S ⁻	Be	1500	55	0.45	26	Cs + CS ₂
Cl ⁻	Be	1500	45	0.50	33	Cs + CCl ₄
Cl ⁻	NaCl	2000	50	0.50	20	Cs + H ₂
CaH ₃ ⁻	50% Ca - 50% Cu	1500	15	0.75	2	Cs + H ₂
TiH ₃	Ti	800	65	0.8	2.5	Cs + H ₂
FeH ⁻	Fe	900	60	0.55	2.8	Cs + H ₂
Ni ⁻	Ni	900	40	0.75	140	Cs + Ar
Cu ⁻	Cu	1000	45	0.75	80	Cs + Ar
Se ⁻	CdSe	1000	40	0.40	7.8	Cs + Ar
ZrH ⁻	Zr	1000	60	0.50	0.2	Cs + H ₂
Ag ⁻	Ag	950	37	0.55	36	Cs + H ₂
Pt ⁻	Pt	1100	35	0.6	40	Cs + H ₂
Au ⁻	Au	1000	100	0.4	100	Cs + Ar

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Figure Captions

- Fig. 1. The improved radial geometry cesium plasma negative ion source.
- Fig. 2. Computational analyses of the negative ion extraction region of the radial geometry cesium plasma negative ion source for cathode radii of (a) 15-mm and (b) 23-mm, respectively. The emission current density is $200 \mu\text{A}/\text{cm}^2$ for both cathodes.
- Fig. 3. The relationship between cesium oven heater current and cesium oven temperature.
- Fig. 4. Total negative ion yield for Cu^- and Ni^- as a function of cesium oven temperature.
- Fig. 5. Relative negative ion yields for Cu^- , Ni^- , Se^- and FeH^- as a function of sputter probe voltages.

(a) EXISTING ION OPTICS: $j = 0.2 \text{ mA/cm}^2$; $\theta_{\text{rms}} = 2.33^\circ$

(b) PROPOSED LOW ANGULAR DIVERGENCE ION OPTICS: $j = 0.2 \text{ mA/cm}^2$; $\theta_{\text{rms}} = 0.79^\circ$