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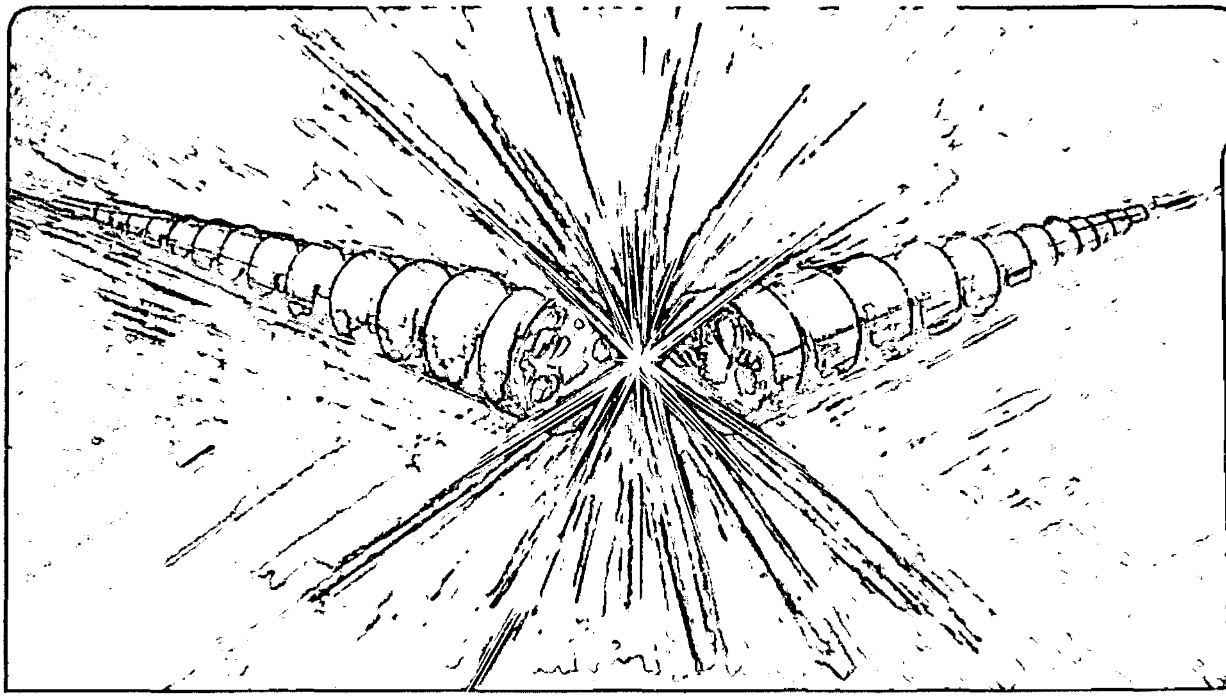

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H- PRODUCTION FROM NON-CESIATED CONVERTER-TYPE NEGATIVE ION SOURCES*

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ABSTRACT

Recent results of surface produced negative ions are presented. Two low work function metal surfaces have been studied, barium and magnesium, in combination with several plasma generators; RF- and DC-filament discharges. The negative ion yield for barium is about 5 to 6 times larger than magnesium. This ratio is confirmed by model calculations on resonant charge exchange.

INTRODUCTION

The two fundamentally different techniques to produce or generate negative ion beams are generally referred to as *volume production* [1,2] and *surface conversion.*[3,4] Each technique has its specific advantages and drawbacks and at the moment it is not clear which technique will prove the most useful. Therefore, a large research effort is still dedicated to the development and understanding of both production methods. This paper discusses the ongoing research in the field of surface conversion at Lawrence Berkeley Laboratory with two separate research objectives: (i) An experimental and theoretical survey of low work-function metals applicable in a surface conversion source and (ii) a study of the integration of plasma generation with surface production.

One of the first surface conversion experiments was done by Belchenko et al., who extracted a beam of negative hydrogen ions from a magnetron source.[5] Some of these ions were produced on the cathode surface. It was generally believed that the conversion process taking place at the cathode could be better controlled if it was separated from the plasma production process. Therefore, in most subsequent experiments the negative ions are produced on an isolated electrode, the so-called converter.[6,7,8,9] In a typical surface-conversion negative-ion source, the converter is biased at a negative potential of a few hundred volts, so that it draws a flux of positive hydrogen ions from the surrounding plasma. A fraction of these ions is back-scattered and some cause adsorbed hydrogen atoms to be sputtered from the converter surface. The back-scattered and sputtered hydrogen atoms can form negative ions via electron capture from the metal surface. Negative ions thus formed are accelerated across the

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plasma sheath and are "self-extracted" from the source.[4] The formation process is operative over a distance of a few times the Bohr radius, a_0, which is small with respect to the sheath thickness. The latter is typically a few tens of a μm in an intense discharge. Therefore, the charge exchange process between metal surface and hydrogen atom is not influenced by the sheath potential.

The converter should have a low work function to obtain a high negative ion yield. This can be achieved via adsorption of a sub-monolayer of cesium on a metal substrate.[10] The cesium coverage can be obtained by admitting cesium vapor into the discharge chamber. However, cesium in the source migrates to the accelerator structure and causes electrical breakdown. This encouraged a search for other, less contaminating, methods for producing a low work function surface.

Recent experiments at the FOM institute in Amsterdam showed that, using a pure barium-metal converter, negative ion conversion efficiencies could be obtained that were of the same order as for cesiated surfaces.[11,12,13] The conversion efficiency, defined as the ratio between the produced negative ion current denisty and the positive ion current density striking the converter surface, provides us with a means to compare different types of converter materials in combination with different plasma generators.

The materials we have investigated experimentally are barium, magnesium, copper and molybdenum. The latter two metals are routinely used to verify the operation of the diagnostics, and to provide us with the necessary base line data. Basically three different plasma generators are used; a magnetically confined plasma column (sheet plasma), a filament discharge (employing both tungsten and barium oxide cathodes) and a radio-frequency discharge (operating at around 1.7 MHz). This paper reports on the results obtained so far and compares the conversion efficiencies with calculated ionization probabilities for the various metals used in the experiments.

THEORY ON SURFACE CONVERSION

Let $\eta_H(v)$ be the velocity dependent probability for a hydrogenic atom leaving a surface to escape as a negative ion. Then the negative ion flux is,

$$J_{H^-} = \int_V dv\ \eta_H(v)\ J_H(v) \qquad [1]$$

where $J_H(v)$ is the flux of hydrogenic particles leaving the surface and the integral is taken over all velocity space with a component that exits the surface.[14,15] In a practical surface conversion source, only negative ions leaving more or less normal to the surface are collected. In view of the difference in angular distribution of sputtered and reflected particles, $J_H(v)$ can be simplified with the assumption that only sputtered or recoiled hydrogen atoms contribute.[16,12] Both processes result in hydrogen atoms leaving the surface with a relatively low energy, of the order of a few tenth's of an eV. This reduces the integration in Eq. [1] to a small energy range which can be further simplified by assuming that the particles leave with an average energy <E>;

$$J_{H^-} \approx \eta_H(\langle E \rangle)\ J_H^* \qquad [2]$$

Here <E> represents the average energy of the sputtered and other low energy particles and J_{H^*} the sputtered flux. The latter is equal to the incident flux of positive particles on the converter multiplied by a coefficient, $\Gamma_{H\text{-}H}$ which determines the stimulated desorption or sputtered yield;

$$J_{H^*} = \Gamma_{H\text{-}H} J_{H^+} \qquad [3]$$

For a solid body metal converter (e.g. Barium), van Os, van Amersfoort and Los have argued that the coefficient $\Gamma_{H\text{-}H}$ is equal to the sputter coefficient multiplied by a probability of hitting a hydrogen atom sitting in the surface layers.[13] The latter probability is assumed to be equal to the relative hydrogen concentration in the surface layers. A comparison of different converter surfaces in terms of conversion efficiency gives an indication of whether relative hydrogen concentrations differ for different converter materials, provided that the ionization probability in Eq. [2] is known for these materials. In the following, we will briefly discuss a model with which this ionization probability can be calculated.

The process of forming a negative ion via interaction with a low work function surface is generally referred to as a "resonant" charge exchange.[17,18,19,20] The electron affinity of a negative hydrogen ion increases when it comes into the vicinity of a metal surface because of the attractive interaction with its image in the metal plane. This lowering of the potential well can be expressed as a function of the atom metal surface separation, z, by a $0.25\,(z + k_s)^{-1}$ dependence, where k_s denotes the screening length of the metal electrons expressed in atomic units.[21] Due to this lowering, at short distances, the potential drops below that of the metal surface. At this point electrons from the metal may tunnel through the potential barrier and be shared between the metal surface and the ion. The tunneling frequency depends exponentially on the height and the width of the barrier. In other words, electrons tunnel between the hydrogen atom and the metal conduction band with a certain transition frequency $\omega(z)$ which is an exponentially decaying function of the distance, z, between atom and metal.

Via this process of resonant population, the atom has a certain charge probability, $N^-(z)$, in the vicinity of the surface. When this atom moves away from the surface, this probability decays, depending on the normal velocity of the atom and the transition frequency. If the atom moves very slowly, almost adiabatically, it will lose all of its charge. On the other hand if the atom moves too rapidly with respect to the transition frequency no charge will be transferred and no negative ion will be formed. In the intermediate range we expect some probability of forming a free negative ion. This formation probability can be calculated using the stationary phase approximation which yields[22]

$$\eta_{H^-}(v_\perp) = \frac{1}{v_\perp} \int_{z_0}^{\infty} N^-(z)\omega(z)\exp\left(\frac{-1}{v_\perp}\int_{z}^{\infty}\omega(z')dz'\right) dz. \qquad [4]$$

Where $N^-(z)$ is an occupation probability depending mainly on the position of the affinity level with respect to the Fermi level, and $v_\perp$ represents the normal component of velocity of the hydrogen atom. Note, this expression has constraints on the region over which it is valid. However, it has been shown that meaningful results can be obtained with this model for the metal surfaces considered here.[23,24] With this expression, the free negative-ion production probability can be calculated as a function of the energy of the hydrogen atom leaving normal to the surface.

Using the experimental data from scattering experiments at grazing angles of incidence, van Os et al. were able to determine the screening length and use Eq. [4] to calculate the production probability; as has been done previously for cesiated surfaces.[25],[26] For barium a value of 2.4 a_0 for the screening length has been reported. This value is about 1 a_0 longer than a value based on the assumption that the affinity level of the hydrogen atom should join the bottom of the conduction band at zero atom-metal separation. Since no experimental data is available for the other materials we are interested in, we added this difference of 1 a_0 to the previous values to calculate the production probability at the surface of these metals. Since most of the metals are in the alkali earth metal group, it is anticipated that this is a reasonable assumption. In Figure 1 we have collated the results of these calculations for barium, magnesium, strontium, copper and lithium for a 'normal' energy ranging from 1 to 20 eV. The calculated probabilities for barium and strontium more or less coincide, which was expected in view of the minor differences in their electronic properties.[27] The H^- production

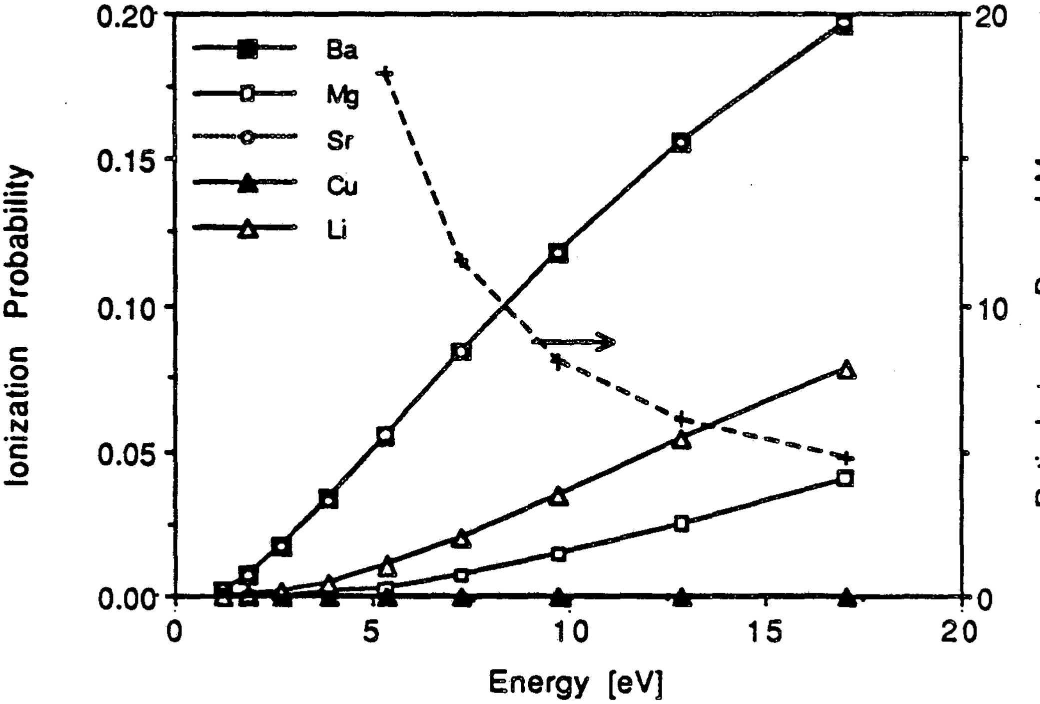

Fig. 1. The calculated production probability for the formation of a negative hydrogen ion as a function of the energy with which the atom leaves normal to the surface for five different metals. The dotted line represents the ratio in ionization probability for barium and magnesium.

probability for copper in this energy range is less than 10^{-4}. The calculated results for molybdenum are not plotted but are essentially the same as for copper. So far, experimental data has been obtained for barium, magnesium and copper surfaces. Therefore, the ratio of the probabilities for barium and magnesium is also shown in Figure 1 for comparison with experimental data.

EXPERIMENTS

This section is subdivided in three parts which describe the set-up, operation and results of individual experiments related to surface conversion using a barium and a magnesium metal converter. The source pressures are all of the order of 1 mTorr and, before measurments, the converters are routinely cleaned by argon sputtering.

I. RF-Plasma generation

A pulsed radio-frequency discharge, with a pulse length of 1 ms and a repetition rate of about 100 Hz, is created in a multicusp bucket with a diameter of 15 cm. The set-up is schematically shown in Figure 2. The antenna is made of anodized aluminum and connected to the RF generator using a matching network. The RF frequency is around 1.7 MHz. The surface produced negative ion current is analyzed with a small 180° magnetic analyzer located just behind a 1 mm extraction aperture. No extraction voltage is applied, so the analyzer collects only self-extracted negative ions.

Since these ions are formed as a result of incident positive ions that desorb or sputter hydrogen atoms located at the surface layers, it is worthwhile to measure the

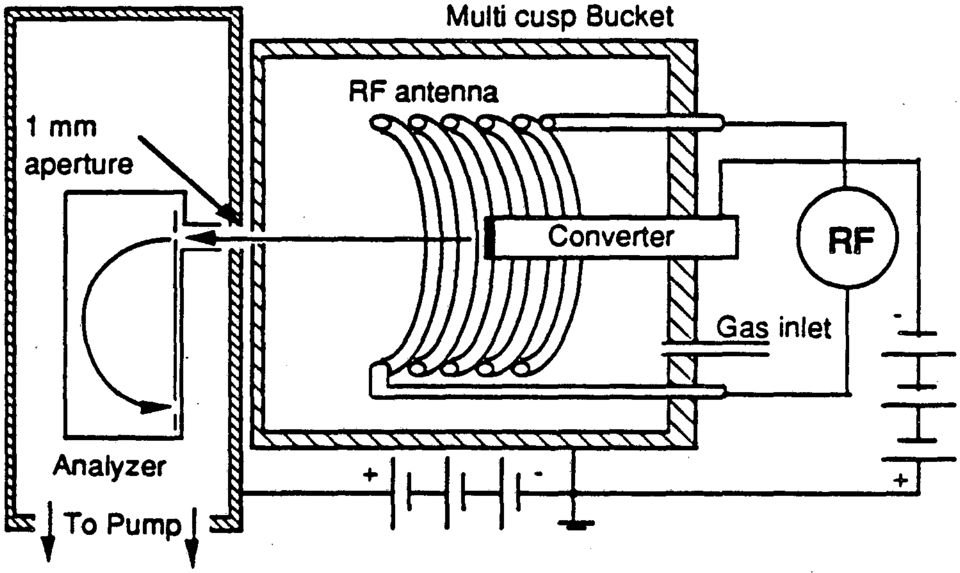

Fig. 2. Schematic diagram of the RF plasma generator. Also shown is the position of the biasable converter and the magnetic analyzer.

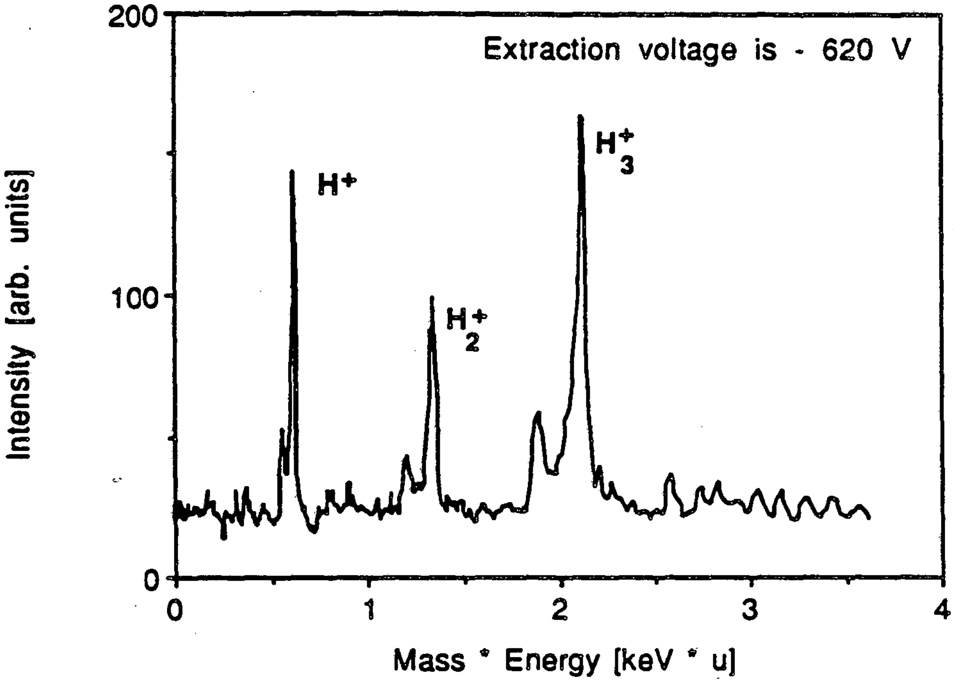

Fig. 3. The energy distribution of positive ions directly extracted from the RF plasma bucket. The energy resolution of the analyzer is of the order of 0.5 %.

energy distribution of the ions hitting the surface. This has been done by applying a positive extraction voltage to the source and using the magnetic analyzer to measure the square of the momentum of the extracted ions as depicted in Figure 3. The structure of the positive ion peaks resembles that found for positive ions extracted from a capacitively-coupled RF-discharge. The observed structure in the energy distribution, which should also be present for positive ions impurging upon the negatively biased converter, results in a less well defined incident energy on the converter surface. However, it is only a small fraction of the total incident energy.

Figure 4 shows the energy distributions of self extracted ions for a barium converter biased at -200 V and a magnesium converter biased at - 400 V. In the present set-up the bias on the Ba converter was limited to -200V to minimize the formation of converter spots. With a magnesium converter biased at -200 V the average area under the sputtered peak for several measurements was compared with an average for the barium converter. The ratio in peak area for the barium surface and the magnesium surface was 6.6 ± 3. Note, that the energy distribution for a barium converter is dominated by sputtered particles whereas the equivalent distribution for magnesium is not. This is because of the higher probability for forming low energy negative hydrogen ions in the vicincity of a barium surface.

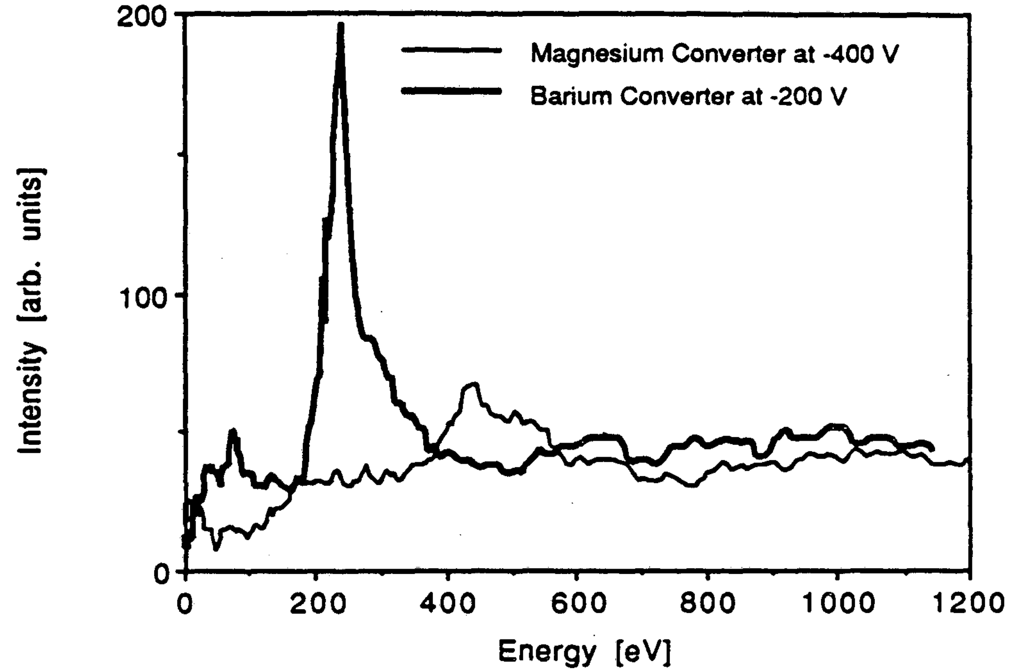

Fig.4. The energy distribution for the "self-extracted" negative ions for a barium (thick line) and a magnesium (thin line) converter. The source operating conditions are the same in both cases.

II. Discharges with thermionic emitting cathodes

An arrangement similar to the one shown Figure 2 is employed, without the RF antenna and with a multicusp bucket with a diameter of 15 cm. The same analyzer is used for measuring the energy distribution of the surface produced negative ions. The bucket can be equipped either with a tungsten filament or a barium oxide cathode. With the tungsten filament installed we measured the energy distribution for a barium converter as a function of its bias, as depicted in Figure 5. These spectra confirm that a large fraction of the negative ions are produced by ion impact stimulated desorption (sputtering and recoiling).[28] Furthermore, the increase in converter bias tends, preferentially, to increase the desorbed fraction of the negative ion yield.

The same bucket has been used to measure the energy distribution for a magnesium converter. The result of this measurement is depicted in Figure 6 together with the data for barium. The ratio in peak area, obtained using the method described in the previous section, is 4.6 ± 1.5 at a converter bias of -400 V.

In doing the experiments it appeared that the results are very sensitive to the preparation method of the converter surfaces and how well one is able to clean the surface in-situ. This led to the suspicion that the material coming from the tungsten filament was contaminating the surface. Therefore, the bucket was operated with a barium oxide cathode to check the extent of this contamination. This cathode is an ohmically heated, coaxially driven, porous tungsten cylinder impregnated with barium

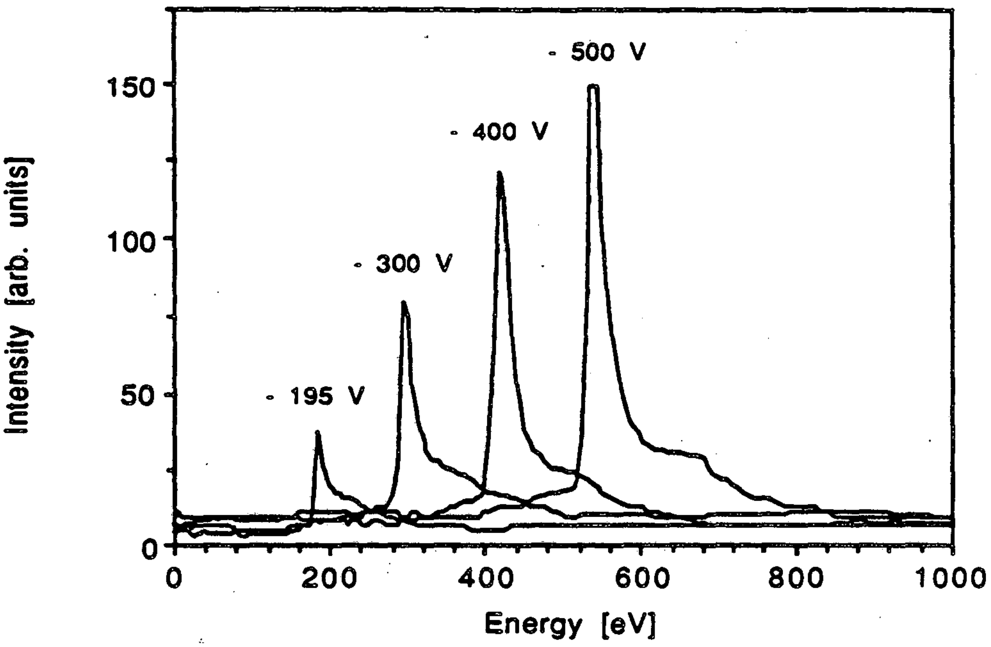

Fig. 5. The energy distributions of the self extracted negative ions for a converter bias ranging from -195 V to -500 V. The source pressure is of the order of 1 mTorr and a moderate arc current of 10 A

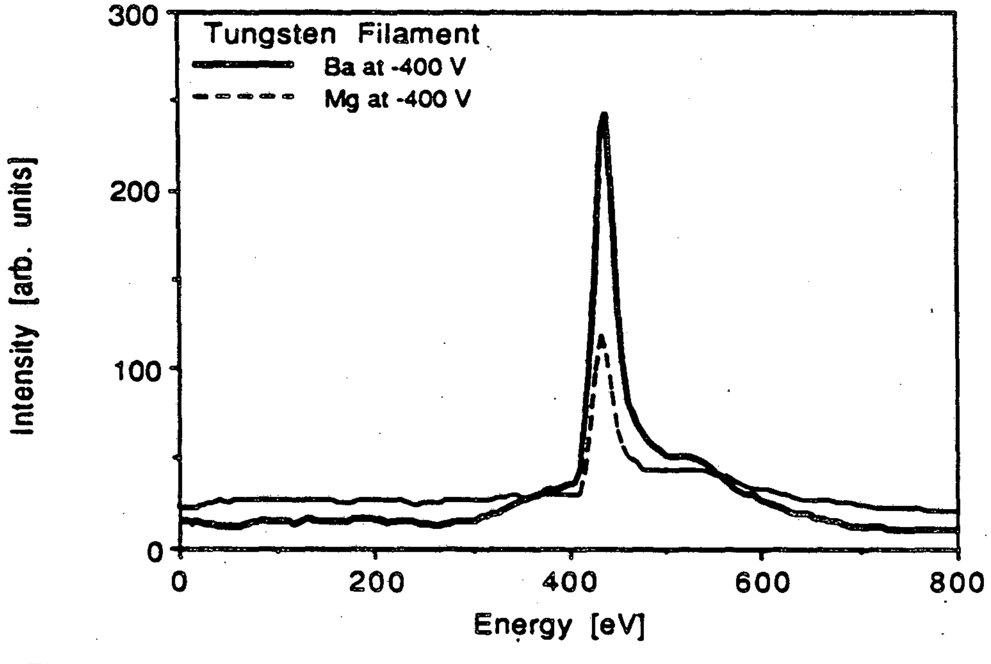

Fig. 6. The energy distribution of the self extracted negative ions for a converter bias of -400 V for a barium and a magnesium surface. Operating conditions are the same as Figure 5.

oxide, that is of similar construction as cylindrical LaB_6 cathodes previously reported.[29,30] The energy distribution, obtained with this cathode, for a converter bias of -220 V is depicted in Figure 7 along with the previously determined distribution for a barium converter biased at -195 V employing a tungsten filament. There is a distinct difference in shape but the yield is of the same order which indicates that the tungsten contamination problem is not serious at the low power levels used for thesemeasurments.

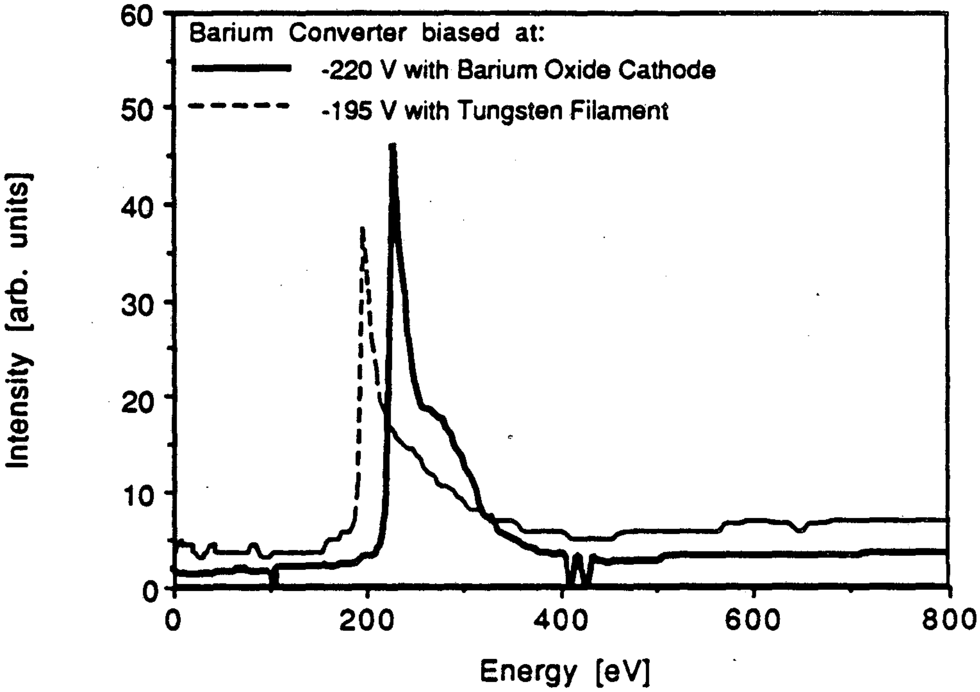

Fig. 7. The energy distribution of the self extracted negative ions for a converter bias of the order of -200 V for a barium converter operated in a bucket equipped with a tungsten filament and a barium oxide cathode. Operating conditions are the same as Figure 5.

III. Sheet Plasma discharge

A different approach to reduce the surface pollution due to material evaporated and sputtered from the emitting cathode is to position it far from the converter and create a magnetically confined plasma column. The arrangement used is essentially a variation of an Uramoto sheet plasma source[31] modified to permit a converter in the vicinity of the column. A schematic arrangement of the converter module and negative ion collector are shown in Figure 8. The negative ion accelerator has an aperture of 1 cm^2, and the converter we used was 2.5 cm in diameter. The obtained negative ion current density as a function of the arc current are depicted in Figure 9. The positive ion current density ranges from 50 mA/cm^2 for an arc current of 10 A, to 400 mA/cm^2 for 60 A.

The associated conversion efficiencies are 2.5 % for barium and 0.45 % for magnesium for a positive ion current density of 50 mA/cm^2. For larger positive ion current densities the conversion efficiency for barium and magnesium drop to a value of 0.7 % and 0.13 %, respectively. This drop in conversion efficiency with increasing positive ion current density is in sharp contrast with the results obtained at the FOM Institute in Amsterdam,[13] who reported an increase of the conversion efficiency with increasing positive ion density. We attribute this scaling difference to the higher electron temperature and higher primary electron density observed in the LBL sheet plasma. Both aspects will increase the barium ion density in the discharge and the the barium ion bombardment (and sputtering) of the converter surface. This is suspected of having two deleterious effects upon the delivered negative ion current. i) The presence of barium ions in the discharge is expected to noticeably increase the ion and electron density immediately in front of the converter, thereby aggravating the negative ion destruction processes[32], and (ii) the increased barium ion bombardment of the surface is postulated to reduce the (target) density of accumulated hydrogen in the surface layers. The hydrogen atoms desorbed in this process are believed to be to slow to have a significant probability for forming a negative ion.[13] Both effects are increasing functions of plasma density and converter voltage. Further work is needed to unravel the relative influences of the two mechanisms.

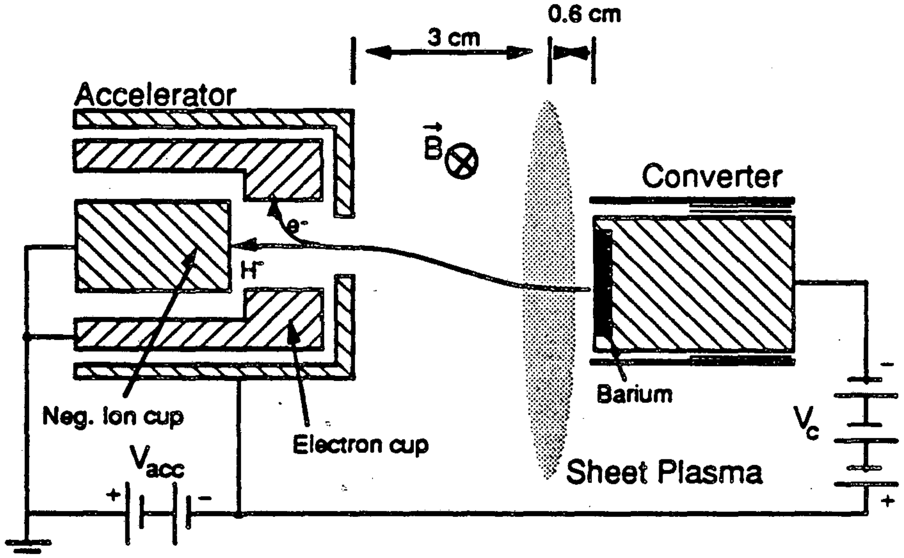

Fig. 8 Detail of the experimental arrangement of the converter and diagnostics.

The ratio of the negative ion current density for barium and magnesium, at a converter bias of -200 V, amounted to 5.2 ± 0.6. This ratio agrees with the value obtained from the RF source which was taken at the same converter bias.

CONCLUSIONS

The contamination problem of the active low work function surface (converter) can be avoided in different ways. The use of a RF plasma is clearly favorable if one is able to create sufficiently high plasma densities to feed the converter with enough positive ions. The RF created plasma shields the converter sufficiently to prevent direct coupling of the RF field to the converter and support structure. A second approach is to place the filaments out of sight of the converter surface to inhibit material from being depositied. However, ionized cathode material may sill reach the converter and contaminate the surface. This resulted in a third alternative; the use of a cathode made of the same material as the converter itself. However, too many heavy ions in the discharge can reduce the negative ion yield either through stripping collisions or depletion of the surface-accumulated hydrogen.

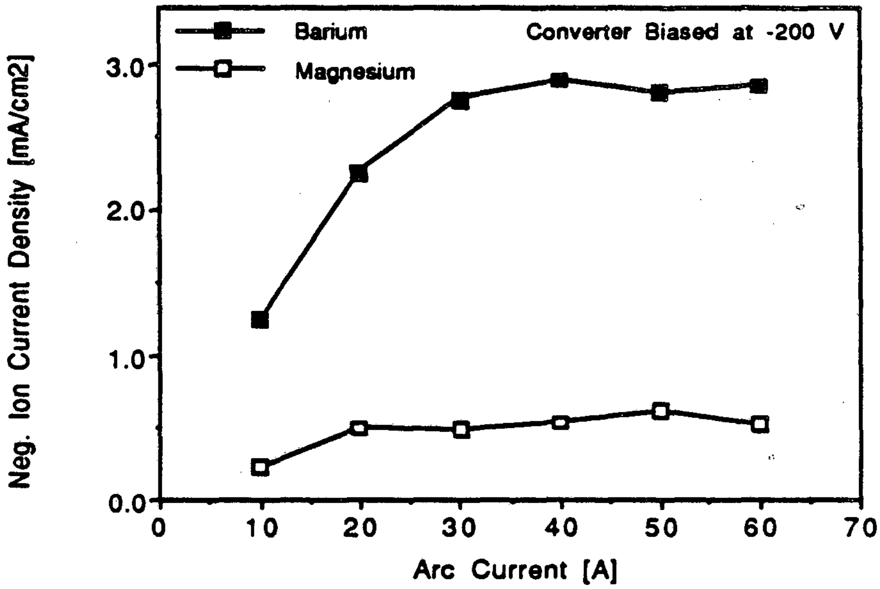

Fig. 9. The self extracted negative ion current density vs arc current. The source pressure is 2 mTorr, the arc voltage -80 V, the converter voltage -200 V, the acceleration voltage 3.3 kV, the distance between converter surface and sheet center is 0.6 cm and for the accelerator this distance is 3 cm.

Qualitatively, the empirically determined ratios of the negative ion yield for barium and magnesium, follow the trend in the calculated ratios in attachment probability, depicted in Fig. 1, with energy. However, qualitatively the empirical ratios are lower when compared to the theoretically determined ratios. The latter observation might we attribution to a different behavior in terms of the hydrogen desorption yield upon ion impact.

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