Estimation of Sputtering Damages on a Magnetron H- Ion Source Induced by Cs+ and H+ Ions

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An H⁻ ion source is being developed for CERN's Linac4 accelerator. A beam current requirement of 80 mA and a reliability above 99% during 1 year with 3 month uninterrupted operation periods are mandatory. To design a low-maintenance long life-time source, it is important to investigate and understand the wear mechanisms. A cesiated plasma discharge ion source, such as the BNL magnetron source, is a good candidate for the Linac4 ion source. However, in the magnetron source operated at BNL, the removal of material from the molybdenum cathode and the stainless steel anode cover plate surfaces is visible after extended operation periods. The observed sputtering traces are shown to result from cesium vapors and hydrogen gas ionized in the extraction region and subsequently accelerated by the extraction field. This paper presents a quantitative estimate of the ionization of cesium and hydrogen by the electron and H⁻ beams in the extraction region of BNL's magnetron ion source. The respective contributions of Cs⁺ and H⁺ ions to the sputtering process are estimated.

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Abstract. An H^- ion source is being developed for CERN's Linac4 accelerator. A beam current requirement of 80 mA and a reliability above 99 % during 1 year with 3 month uninterrupted operation periods are mandatory. To design a low-maintenance long life-time source, it is important to investigate and understand the wear mechanisms. A cesiated plasma discharge ion source, such as the BNL magnetron source, is a good candidate for the Linac4 ion source. However, in the magnetron source operated at BNL, the removal of material from the molybdenum cathode and the stainless steel anode cover plate surfaces is visible after extended operation periods. The observed sputtering traces are shown to result from cesium vapors and hydrogen gas ionized in the extraction region and subsequently accelerated by the extraction field. This paper presents a quantitative estimate of the ionization of cesium and hydrogen by the electron and H^- beams in the extraction region of BNL's magnetron ion source. The respective contributions of Cs^+ and H^+ ions to the sputtering process are estimated.

Keywords: negative ion source, H^- , Cesium, sputtering damages.

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INTRODUCTION

Linac4 is a 160 MeV H^- linear accelerator planned to replace the existing Linac2 as an injector to the Proton Synchrotron Booster (PSB). Linac4 aims at doubling the beam brightness out of the PSB, thus allowing an upgrade of the Large Hadron Collider (LHC) injectors for higher intensity and eventually an increase of the LHC luminosity [1].

CERN's Linac4 accelerator is under construction and a RF driven H^- ion source is being developed. The beam current requirement for Linac4 is 80 mA. A cesiated plasma discharge ion source, such as the BNL (Brookhaven National Laboratory) magnetron source is a candidate if proven to operate at the required 0.8 to 2 Hz repetition rate at 45 kV extraction voltage. The ion source must achieve reliability above 99 % so it is necessary to investigate and understand the mechanisms leading to source failure and ageing. In the BNL magnetron surface ion source, erosion of the molybdenum cathode and stainless steel anode cover plate surfaces is visible after extended operation periods [2]. Sputtering traces on these surfaces result from positive ions created in the extraction region by beam impact on the residual gas, and subsequently accelerated by the extraction field. This paper estimates the ionization rate of cesium vapors and hydrogen in the extraction

FIGURE 1. BNL magnetron (a) scheme and (b) detail of the extraction region. Location of the sputtering traces on the cathode and anode cover plate are indicated by an ellipse with horizontal major axis and an ellipse with vertical major axis (red and green), respectively.

region and tracks the resulting ions in the electric and magnetic fields of the source.

BNL MAGNETRON SOURCE

BNL's magnetron operates at 7.5 Hz and delivers H^- pulses with 0.7 ms duration, up to 100 mA at 35 kV [3]. A scheme of the magnetron source is shown in Fig. 1 (a) and a detail of the extraction region with dimensions is presented in Fig. 1 (b).

Table 1 shows the typical operation parameters of the BNL magnetron source, such as the beam current, time constants and the consumption of cesium and hydrogen during operation. Linac4 ion source requirements are shown for comparison.

Figure 2 shows the erosion of material on a magnetron that successfully operated for 2 years [2]: the cathode has a hole of 1.8 mm^2 close to the center of its spherical focusing dimple and the anode cover plate shows marks in the vicinity of the extraction hole spread in an area of 62 mm^2 .

TABLE 1. Nominal operation parameters for the BNL magnetron source and Linac4.

	BNL	Linac4
H^- current (mA)	90-100	80
Electron current (mA)	45-50	-
Repetition rate (Hz)	7.5	0.8-2
Pulse width (μs)	700	500-600
Duty factor (%)	0.5	0.04-0.12
Extraction voltage (kV)	35	45
Cs consumption (mg/h)	< 0.5	-
H_2 gas flow (sccm)	2.0	-
Normal rms emittance (mm mrad)	0.4	0.25

FIGURE 2. Wear traces on the (a) cathode and (b) the anode cover plate of BNL's magnetron. The location of the traces on the cathode and anode cover plate is indicated by a circle and an ellipse (red and green), respectively.

HYDROGEN AND CESIUM VAPORS IONIZATION PROCESS

The H^+ and Cs^+ yields in the extraction region are estimated from the interaction of the H^- and electron beams with the cesium and hydrogen molecules in the volume between the anode and the puller electrode. In this region, only positive ions are accelerated from the puller to the anode and cathode of the magnetron H^- ion source. The volumes of the electron and H^- ion beams are highlighted in Fig. 3 being approximated by a cylinder for the hydrogen ion beam and a frustum of a cone for the electron beam. The cylinder is 4 mm long and the anode cover plate extraction hole diameter is 2.8 mm. The cone frustum is 4 mm long, the largest radius is 1.4 mm and the smaller radius is 1.04 mm.

FIGURE 3. (a) BNL magnetron extraction region: H^- and electron beams as simulated with IBSimu software [2]. The volumes considered for the ionization of positive cesium and hydrogen ions are indicated: (b) a cylinder for the H^- beam and (c) a cone frustum for the electrons.

The ionization yield (n_{ion} in number of ions per second) in the extraction volume of BNL magnetron source is summed over the various ionization processes (H^- and electron impact on atomic cesium or hydrogen), according to Equation (1).

$$n_{ion} = \sum_{j,i}^n \varphi_j \sigma_{j,i} \rho_i S_i L \quad (1)$$

φ_j is the flux of the ionizing beam (in $cm^{-2} s^{-1}$), $\sigma_{j,i}$ is the cross section of the interaction (in cm^2), ρ_i is the rest gas average density (in cm^{-3}), S_i is the interaction volume transversal section (in cm^2) and L is the interaction length (in cm). The index j stands for the H^- or electron beam and i corresponds to the H_2 and cesium vapor present in the extraction region.

The beam used for calculations is 100 mA of H^- and the ratio of e/H^- equal to $1/2$ leads to a 50 mA current of electrons [3], as given in Table 1.

Table 2 lists the cross section for the reactions of H^- ions and electrons with cesium and hydrogen, leading to positive ions. Since there is no available data for the reaction between H^- and H_2 , the cross section for the reaction of H^+ with H_2 is used. Reactions with cross sections of lower orders of magnitude are not taken into account. The reaction energies are indicated; 20 keV is used as the maximum energy for the interaction assuming that higher energy interactions lead to the resulting ion proceeding forward rather than being accelerated back.

The average density ρ_i (in cm^{-3}) of the target particles H_2 and Cs is obtained from Equation (2).

$$\rho_i = \frac{\dot{m}_i N_A / M_i}{v_i S_i} \quad (2)$$

$\dot{m}_i$ is the mass flow rate of the cesium and hydrogen released through the anode extraction hole (in $g s^{-1}$), v_i is their mean velocity (in $cm s^{-1}$), S_i is the cross section area (in cm^2) of the volume that encompasses the projectile particles, M_i is the atomic weight of the target (in $g mol^{-1}$) and N_A is the Avogadro's constant.

TABLE 2. List of cross sections leading to the production of positive ions via impact of energetic H^- ions or electrons on cesium and molecular hydrogen. Beam energies are indicated.

Reaction	Energy (keV)	Cross section (cm^2)	Source
$e^- + Cs \rightarrow Cs^+ + 2 e^-$	20	15.0×10^{-16}	[4]
$H^- + Cs \rightarrow H^+ + 2 e^- + Cs$	20	1.3×10^{-16}	[5]
$H^+ + H_2 \rightarrow H^+ + H_2^+ + e^-$	20	7.3×10^{-17}	[6]

TABLE 3. Calculated properties of the target particles and resulting ion production rate during pulses.

	Velocity ($m s^{-1}$)	Flow rate (s^{-1})	Density (cm^{-3})	Positive ion yield ($ion s^{-1}$)
Cs	3.54×10^2	6.50×10^{14}	2.98×10^{11}	4.3×10^{13}
H_2	2.88×10^3	9.09×10^{17}	5.12×10^{13}	9.4×10^{14}

The rest gases mean velocity along the interaction volume is obtained by equation (3).

$$v_i = \sqrt{\frac{k T_i}{m_i}} \quad (3)$$

T_i is the assumed temperature (in K), m_i is the mass of the gas particle (in kg) and k is the Boltzmann constant (in $\text{kg m}^2 \text{s}^{-2} \text{K}^{-1}$).

The results of the flow rate value for the cesium and hydrogen, their mean particle velocity and density are summarized in Table 3, for an arbitrary temperature of 2000 K. Using the approximate values given in Table 1, 2 and 3, the resulting ion yield of H^+ (9.4×10^{14} ion/s) is a factor 20 higher than the yield of Cs^+ (4.3×10^{13} ion/s).

EXTRACTION ELECTRODES SPUTTERING RATE

The sputtering rate (S_{kl} in nm min^{-1}) caused by a positive ion (k) on a molybdenum or stainless steel electrode (l) is determined from equation (4).

$$S_{kl} = \frac{6.23 J_k M_l \langle Y \rangle_{kl}}{\rho_l} \quad (4)$$

J_k is the ion current density (in mA cm^{-2}), M_l is the electrode material atomic weight (in g.mol^{-1}), $\langle Y \rangle_{kl}$ is the average sputtering yield (in atom ion^{-1}), ρ_l is the electrode material density (in g cm^{-3}) and 6.23 is a conversion factor (in $\text{mol atom}^{-1} \text{ion mA}^{-1} \text{min}^{-1} \text{mm cm}^{-1}$) [7].

Considering the current of positive ions created in the extraction area, the ion current density is calculated. IBSimu simulation showed that 67 % of the positive ion current hits the molybdenum cathode and 33 % the stainless steel anode cover plate [2]. All positive created ions hit the plasma electrodes on the area showing wear signs.

The sputtering yield is obtained as a function of the energy using the software SRIM (The Stopping and Range of Ions in Matter) [8].

Figure 4 shows the sputtering rate for the molybdenum cathode by H^+ and Cs^+ as a function of the ions incident energy, assuming they have an energy of 0 to 45 keV, for a perpendicular incidence on the electrode surface. The values presented are for 365 days of source operation at a duty factor of 0.5 %. Figure 5 shows the sputtering rate of the stainless steel anode cover plate in the same conditions.

FIGURE 4. Molybdenum cathode sputtering rate per year of operation at 0.5 % duty factor, as a function of the incident energy of the H^+ and Cs^+ ions, for a perpendicular incidence on the electrode surface.

FIGURE 5. Stainless steel anode cover plate sputtering rate per year of operation at 0.5 % duty factor, as a function of the incident energy of the H^+ and Cs^+ ions, for a perpendicular incidence on the electrode surface.

FIGURE 6. Molybdenum cathode sputtering rate by Cs^+ per year of operation at 0.5 % duty factor, as a function of the incident ion energy, for different incident angles.

The sputter yield is a strong function of the incident angle of the ion on the surface. The approximation of normal incidence is only correct for the cathode where the ions impact close to the beam axis. Nevertheless, different impact angles result from the trajectories of the positive ions on the extraction region, which affects the sputtering of the electrodes. As an example, Fig. 6 shows the variation of the molybdenum cathode sputtering rate caused by Cs^+ , as a function of the incident ion energy, for different ion angles of incidence. For angles above 75° , the variation of the sputtering rate with the angle is not significant. For a 45° ion incidence on the electrode surface, the sputtering rate increases by a factor 2 to 3.

CONCLUSION

The sputter rates of the anode cover plate and cathode of the BNL magnetron H^- ion source, due to ionization of hydrogen gas and cesium vapor have been calculated. It was found that positive cesium ions are the dominant cause of erosion of the molybdenum and stainless steel electrodes when compared to the positive hydrogen ions.

The sputter rates are proportional to the Cs-vapor and hydrogen densities in the extraction region during the H^- ion pulse. The pulsed injection of hydrogen is at the origin of a complex release profile and the amount of atomic cesium released during the ion pulse or from cesium condensed on the nearby surfaces is beyond the scope of this study.

The estimated wear rates of a fraction of a mm per year corresponds to the order of magnitude observed on components operated for few years and scale with the operation duty factor. The magnitude of the estimated wear indicates that the sputtering damage should not prevent the use of the Magnetron H^- ion source and extraction system with the Linac4 specifications.

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