CONCEPTUAL DESIGN OF A SPUTTER-TYPE NEGATIVE ION SOURCE BASED ON ELECTRON CYCLOTRON RESONANCE PLASMA HEATING

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Abstract

A design for a negative ion source based on electron cyclotron resonance plasma heating and ionization by surface sputtering is presented. The plasma chamber of the source is an rf-cavity designed for TE_{111} eigenmode at 2.45 GHz. The desired mode is excited with a loop antenna. The ionization process takes place on a cesiated surface of a biased converter electrode (cathode). The ion beam is further "self-extracted" through the plasma region. The magnetic field of the source is optimized for both, plasma generation by electron cyclotron resonance heating, and beam extraction. The source can be used for a production of a variety of negative ions ranging from hydrogen to heavy ions. The potential users for the source concept range from large scale accelerator facilities, utilizing H^- ion beams, to dc tandem accelerators for heavy ions. The benefits of the source concept compared to widely used filament- and inductively coupled rf-driven sputter-type sources are the lack of consumable parts and low neutral pressure minimizing the stripping losses of negative ions. In this article we will focus on the H^- production scenarios with the novel source. The benefits and drawbacks of higher frequency operations are also discussed.*

INTRODUCTION

The focus of the H^- ion source development program at Los Alamos Neutron Science Center (LANSCE) has recently been on improving the performance of the filament-driven surface conversion ion source (see for example ref. [1]) and developing an rf-driven surface conversion ion source operated with helicon wave mode [2]. The main problems associated with these ion sources are the presence of consumable parts and high neutral gas pressure causing stripping losses, respectively.

In this article we propose a design for a novel H^- ion source based on electron cyclotron resonance plasma heating and surface ionization. The source is expected to operate within a neutral gas pressure range of 0.1-1 mTorr i.e. order of magnitude lower than the helicon discharge [2]. This helps to mitigate the H^- losses due to collisions with neutrals and reduces the volume formation of H^- preventing undesired increase of emittance, sometimes observed with surface converter ion sources [1].

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PHYSICS ASPECTS OF H- ION BEAM PRODUCTION

Modern H^- ion sources are based on two important ion formation processes, the volume [3] and the surface [4] production. The relative importance of these processes depends on the detailed design of the ion source.

The volume production of H^- is generally accepted to be due to dissociative attachment (DA) of low energy electrons to rovibrationally (ν'') excited molecules. Two electron populations are needed in order to optimize the volume production process: hot electrons (few eV) creating the excited molecular states i.e. $e_{hot} + H_2 \rightarrow e + H_2^{v''}$ $(v'' > 5)$ and cold electrons (less than 1 eV) responsible for dissociative attachment i.e. $e_{cold} + H_2^{v''}(v'' > 5) \rightarrow H + H^-$. Therefore, the ion sources based on this process are typically optimized by separating the plasma chamber in two parts by a filter (electrostatic or magnetic) decoupling the plasma heating zone from the H^- production zone (see for example ref. [5]).

The surface production mechanism in negative ion sources is so-called resonant tunneling ionization: the electron affinity level of a hydrogen atom adsorbed on a metal surface shifts and broadens. If the electron affinity level shifts below the Fermi energy of the (cesiated) metal surface, electrons have a finite probability to tunnel through the potential barrier forming an H^- ion when the surface is subjected to heavy ion (Cs) bombardment [7].

The work function of the surface affects the probability of the electron tunneling, which is the other beneficial effect of cesium i.e. Cs deposition lowers the work function. If the bias-voltage of the converter electrode is on the order of hundreds of volts (like in the case of LANSCE converter source) the sputtering of the metal becomes an important issue. This aspect favors the use of converter materials such as molybdenum and rhenium with low sputtering yields under proton bombardment.

In a converter-type ion source the H^- ions created on the cesiated surface have to propagate through the plasma in order to become extracted from the ion source. Three types of loss processes of H^- due to collisions with other particles within the propagated distance need to be considered:

(1) $H^- + e \rightarrow H + 2e$: The H^- mean free path can be calculated from the electron mean free path by taking into account the average velocities (energies) of the particles, $\lambda_{H^-} = \sqrt{\frac{m_e E_{H^-}}{m_{H^-} E_e}}\lambda_e$. This equation was used for estimating the H^- losses due to collisions with electrons for the proposed ion source design.

(2) $H^- + H_2 \rightarrow H^0$ (it is assumed that the neutral hydrogen is in molecular form): A typical neutral gas pressure in an ECR-heated plasma (at 2.45 GHz) is 0.1-1 mTorr. Based on cross section data from ref. [8] it can be calculated that the H^- losses in this pressure range are less than 10% within a propagated distance of < 10 cm.

(3) $H^- + Cs^0 \rightarrow H^0$: The calculation for H^- losses in collisions with neutral cesium atoms (based on the reported cross section [9]) for an H^- energy of 300 eV suggests that if the neutral pressure of cesium exceeds 0.7 mTorr the loss rate of H^- due to collisions with neutral cesium atoms exceeds the loss rate due to collisions with neutral hydrogen molecules at pressure of about 1 mTorr (of H_2). The cesium vapor pressure in the surface converter ion sources is typically much less than 0.7 mTorr.

Therefore, it is plausible to claim that collisions between H^- and neutral H_2 is the dominant loss mechanism. Reducing the neutral gas pressure in the ion source plasma chamber (compared to existing converter sources) is the most efficient way to increase the extracted H^- beam current. In fact, the ability to reduce the neutral gas pressure (from 5-10 mTorr which is typical for the LANSCE helicon source producing 12 -13 mA of H^- [10]) is the greatest motivation for the novel source design.

Due to the negative bias of the converter electrode the H^- beam is formed in the plasma sheath adjacent to the converter surface and is "self-extracted" from the ion source. The beam is focused to the outlet aperture by shaping the surface of the converter. The formation mechanism of the beam explains the relatively small emittance values typically obtained with a LANSCE-type surface conversion ion sources. The trajectories of the H^- ions are affected by the magnetic field in the region between the converter and the outlet aperture. The magnetic field of the ECR-driven ion source can be optimized for both plasma production and beam extraction.

CONCEPTUAL DESIGN OF THE SPUTTER-TYPE ECR SURFACE CONVERSION ION SOURCE

Negative ion sources (for H^-) based on ECR plasma heating have been designed and built earlier. The approach of Tuske *et. al* has been to separate the main plasma from the H^- production region by a filter magnetic field reducing the electron temperature and, consequently, mitigating stripping losses of negative ions near the outlet aperture. H^- ion beam currents on the order of 5 mA have been obtained with this type of an ion source relying on the volume production mechanism of H^- [5]. The main drawback of this approach is the drop of plasma density, imposed by the filter field, between the two stages of the ion source. This limitation can be overcome with a converter-type ion source. Takagi *et al.* have designed and tested an ECR-driven plasma sputter ion source equipped with a converter electrode [11]. In that source design the converter electrode was used also as an antenna coupling the microwave power with the plasma. Negative ion beam currents of 7 mA were obtained with that source. However, the extracted ion beam contained almost 30 % of impurities (O^- and OH^-) due to required microwave power level (3-4 kW) and subsequent heating of vacuum seals. In order to understand the origin of these problems and to avoid them we used MicroWave Studio [12] to simulate the mode structure excited into the plasma chamber. According to our simulations it seems likely that the plasma chamber of the source described in reference [11] is in fact a multimode cavity. In addition, the resonant frequencies closest to 2.45 GHz deposit significant amounts of energy at the microwave window, which could explain the observed heating of vacuum seals near this location. In order to optimize the ionization process we designed (with MicroWave Studio, MWS eigensolver) the plasma chamber to be a single-mode resonant cavity for TE_{111} eigenmode at 2.45 GHz, which should significantly improve the coupling efficiency of the microwaves compared to the source by Takagi. Variation of this design is used at CERN (ISOLDE) for ionization of noble gas radioisotopes (positive ions) [13].

A schematic drawing of the new ion source is presented in Figure 1. Details such as vacuum seals and water cooling channels or subsystems such as cesium oven are not presented.

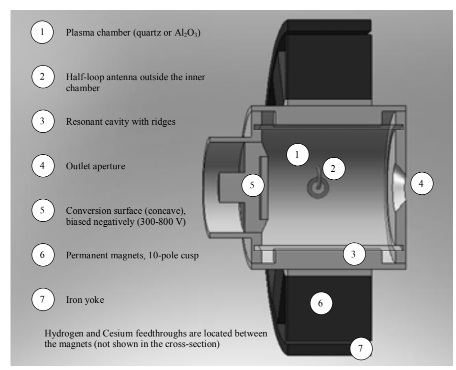

Figure 1. A schematic of the proposed ECR-driven surface conversion ion source.

The plasma chamber of the source is a quartz tube (or aluminum nitride tube for high power, high duty factor operation) located inside a resonant cavity. The quartz tube prevents the plasma to be directly in contact with the antenna and allows the main plasma volume and the remaining cavity volume to be in different vacuum conditions. Two metal ridges with gaps near the end walls are inserted 180 degrees apart on the inner wall of the cavity to allow the magnetic field of the TE_{111} eigenmode at 2.45 GHz, corresponding to a frequency of a cheap commercial magnetron, to complete its loop and to separate it from the unwanted modes, including TM_{010}. The cavity dimensions can be listed as follows: Cavity inner radius 45 mm, cavity length 80 mm, quartz-tube outer radius 37.5 mm, quartz-tube wall thickness, 3.175

mm, ridge width 20 mm, ridge height 7.5 mm, and ridge-end-wall gap length 8 mm.

The desired eigenmode can be exited with a simple loop antenna inserted in the cavity mid-plane, with the loop plane oriented vertically, and connected to a 50-Ω coaxial cable. The magnetic field of the mode is well coupled to the antenna. Figure 2 shows the electric and magnetic fields of the TE_{111} eigenmode excited in the cavity. The presented field normalization is the MWS default, i.e. the field total energy is 1J, which means that the presented values do not correspond to the cavity fields of the operating source.

The effects of the end wall (outlet and biased converter electrode) holes, gaps and shapes were also studied and taken into account in the preliminary design. It was observed that these features had a small effect on the resonant frequency. Also plasma loading of the cavity will slightly affect the resonant frequency. Effects of both kinds can be compensated by tuning the cavity length by moving the converter electrode acting as a tuner.

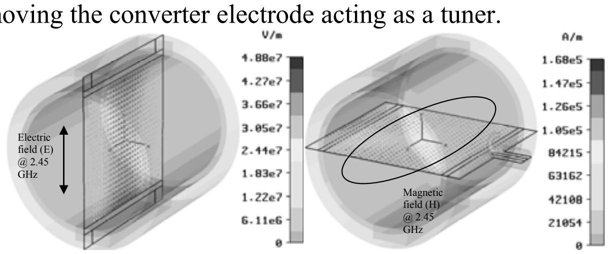

Figure 2. Electric field (left) and magnetic field (right) of the TE111 eigenmode (at 2.45 GHz) excited in the cavity of the proposed ECR-driven surface conversion ion source.

For 2.45 GHz the corresponding resonance magnetic field is 0.0875 T (875 G). The required magnetic field can be generated either with solenoids or permanent magnets. Magnetic field design based on permanent magnets is favorable for two reasons: it makes the source more compact and helps to maximize the extraction efficiency of the H^- ions. In our design ten rows of permanent magnets (NdFeB, grade 50 MGO, 1 inch by 1.5 inch cross section, and length of 2 inches) are placed around the cavity forming a typical 10 pole cusp structure. The resulting resonance surface (B = 0.875 T) is illustrated in Figure 3. The magnetization direction of the permanent magnets is indicated by arrows. The spatial location of the resonance can be varied by moving the magnets in radial direction.

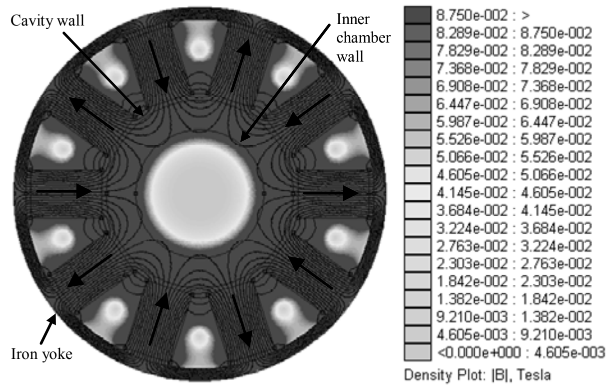

Figure 3. The cusp magnetic field and corresponding resonance surface of the proposed ECR-driven surface conversion ion source. Simulation with FEMM [14].

The magnetic field on the source axis is zero, which is favorable for the beam extraction and for attaining a more uniform plasma density due to $F = -\mu \nabla B$ force "pushing" the electrons (and ions) towards the center of the plasma chamber (cusp confinement). The extraction efficiency was studied with an ion tracking code written with Mathematica. The magnetic field for the ion tracking was simulated with Radia3D [15]. The calculated beam spot at the outlet electrode is presented in Figure 4. The parameters used in this example of ion tracking calculation are: distance from the converter to the outlet 90 mm, converter voltage -500 V, converter radius of curvature 127 mm (concave), converter radius 19 mm. The geometry of the magnetic field is reflected into the shape of the beam spot i.e. number of cusps on the beam spot is half of the number of magnetic poles. Reducing the number of magnetic poles makes the extraction of the H^- more problematic due to increasing magnetic field near the source axis. However, the maximum number of poles that can be used is 10 since for higher number of poles the resonance surface is outside the quartz chamber.

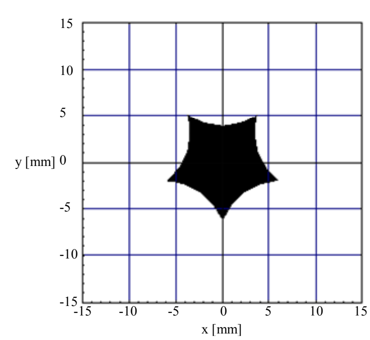

Figure 4. The results of the ion tracking calculation. The "star" represents the predicted beam spot at the outlet aperture.

The energy of the electrons in an ECR heated plasma depends on the neutral gas pressure, microwave frequency and applied power. The electron energy can be reduced by increasing the neutral gas pressure. However, it is desirable for the H^- source application to keep the pressure under 1 mTorr, which not only minimizes the losses due to collisions with neutral particles but also helps to minimize the volume production of H^-. The electron energy distribution is typically a double Maxwellian. It can be expected that the temperature of the dominant electron population is in the order of few eV. The cross section for H^- losses due to collisions with electrons peaks at about 10-20 eV reaching a maximum value of $3\cdot10^{-15}$cm^2. However, the converter electrode voltage can be raised in order to increase the H^- velocity and therefore reduce the losses in collisions with electrons.

The drawback of the design is modest electron confinement, which means that in order to achieve plasma densities on the order of 10^{12} cm^{-3}, relatively high microwave power, on the order of kilowatts, needs to be applied to operate the source in overdense mode.

The deposition of cesium and sputtered material (from the converter) on the quartz tube can have an adverse effect on the coupling of the microwave power with the plasma. This can be mitigated by choosing the right converter material. Rhenium seems to be favorable due to low sputtering yield and high skin depth (compared to other metals). In the worst case if the metal deposition on the quartz tube presents a problem, the tube can be omitted. In this case the antenna needs to be covered by an insulator preventing a direct contact with the plasma. Furthermore the antenna-insulator assembly needs to be shielded from metal deposition. This can be realized with a metal (or dielectric) shield. It is important to isolate the metal shield from the cavity wall in order to prevent the formation of a surface current loop canceling the magnetic field in the antenna region and therefore preventing the coupling of the microwave power to the plasma.

Based on the experience gained with both the LANSCE filament- and helicon-driven surface conversion ion sources we can estimate the expected H^- output for the microwave-driven source presented in this article. Taking into account differences in plasma density, electron temperature and beam dynamics (propagation through the plasma) *we estimate that the H^- ion beam current extracted from the microwave source can be 25-30 mA*. The emittance of the ion beam is mainly defined on the converter surface (sputtering energy of the ions) and, therefore, it can be expected that the emittance of the H^- ion beams extracted from the ECR-driven surface conversion ion source does not differ significantly from the emittance of the LANSCE filament-source (typically 0.15-0.25π mmmrad, 95 % norm.-rms). The expected duty factor of the ECR-driven source is at least 12 %.

Based on the conceptual design and the afore-mentioned estimations we are planning to start construction of the Negative ECRIS (NECRIS) at LANSCE. The goal of the program is to support the ongoing development efforts with the filament- and helicon-driven ion sources and eventually develop a reliable ion source for future missions of LANSCE.

DISCUSSION

The source design presented in this paper can be used for producing other negative ions as well. The converter can be transformed into a cathode manufactured from a material to be ionized. The heavy ion induced sputtering of the cesiated surface will result into emission of negative ions (as in a typical sputter-type ion source based on cesium ionization on hot surfaces). For this purpose the source could be operated in continuous mode. In addition the source concept could be used for the production of intense proton ion beams.

The cusp-ECRIS design could be operated at higher frequency in order to reach higher plasma densities at lower neutral gas pressures. However, the magnetic field design needs to be revisited for this purpose. Using a Halbach-array (with an opening for a coax-input for the antenna) is probably desired if higher frequency operations are pursued. The drawback of using higher frequencies is increased production of X-rays, which requires heavy shielding.

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