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Author(s): O. Tarvainen
S. Kurennoy

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A Proposal for a Novel H^- Ion Source Based on Electron Cyclotron Resonance Heating and Surface Ionization

O. Tarvainen and S. Kurennoy

Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA

Abstract. A design for a novel H^- ion source based on electron cyclotron resonance plasma heating and surface ionization 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. The H^- ion beam is further "self-extracted" through the plasma region. The magnetic field of the source is optimized for plasma generation by electron cyclotron resonance heating, and beam extraction. The design features of the source are discussed in detail and the attainable H^- ion current, beam emittance and duty factor of the novel source are estimated.

Keywords: Negative Ion Source, Electron Cyclotron Resonance Plasma Heating.
PACS: 29.25.Ni, 52.25.Jm

INTRODUCTION

The focus of the H^- ion source development program at Los Alamos Neutron Science Center (LANSCE) has recently been on gradually improving the performance of the filament-driven surface conversion ion source (see e.g. Ref. 1) and developing an rf-driven surface conversion ion source operated in helicon wave mode[2] (see also elsewhere in these proceedings). The benefit of the helicon-driven H^- ion source over the filament-driven source is higher plasma density and longer lifetime. However, the neutral gas pressure required for plasma ignition causes significant H^- losses, as the ions travel through the plasma from the converter electrode to the outlet aperture, which limits the performance of the ion source.

In this article we present a novel design for an 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. This helps to mitigate the H^- losses due to collisions with neutrals and reduces the volume formation of H^- preventing undesired increase of emittance, which is sometimes observed with surface converter ion sources[1].

Physical processes relevant for the H^- ECR ion source are discussed. The source concept is briefly compared to both filament-driven surface conversion source (used for beam production at LANSCE) and the prototype helicon-driven source. This is done in order to estimate the attainable H^- ion current, beam emittance and duty factor of the novel source. The design features and options for the new source concept are discussed and compared to earlier work by other authors.

PHYSICAL PROCESSES AFFECTING THE H^- ION BEAM PRODUCTION WITH SURFACE CONVERSION ION SOURCES

In this chapter physical processes affecting the formation of H^- ions on the conversion surface and the loss processes of H^- in the plasma are discussed in detail together with a brief description on the beam formation. The purpose of the discussion is to highlight the advantages of the new source design and to help estimate the presumably attainable H^- beam currents.

Surface Properties of the Conversion Surface Affecting the H^- Yield

The surface production of H^- ions via resonant electron tunneling on the surface of the converter electrode depends on several factors such as work function, Fermi energy and shifting/broadening of the electron affinity level. The most straightforward way of improving the conversion efficiency (H^- ions/bombarding ions) of the surface is to lower its work function by depositing a fractional monolayer of alkali metal (cesium) on the surface. In filament-driven surface conversion sources the metal surface of the converter electrode is subject to tungsten (or tantalum) deposition due to evaporation of the filaments. The inherent benefit of microwave-driven ion source is the lack of consumable parts in the plasma volume. Therefore, the "tungsten poisoning" of the conversion surface can be avoided meaning that this type of ion source could eventually provide better conversion efficiencies than the state-of-the-art filament sources.

Loss Processes of the H^- Ions

The H^- ions ejected from the conversion surface must travel through the plasma in order to become extracted. In LANSCE filament- and helicon-driven sources the distance from the converter electrode to the outlet is 12 cm and the typical energy of the ions is 225-325 eV corresponding to the negative voltage of the converter electrode (plasma potential is on the order of few volts and therefore negligible). Three types of loss processes of H^- due to collisions with other particles within this distance need to be considered:

(1) $H^- + e \rightarrow H + 2e$: The H^- mean free path λ_{H^-} can be calculated from the following equation: $\lambda_{H^-} = \sqrt{\frac{m_e E_{H^-}}{m_{H^-} E_e}} (\sigma n_e)^{-1}$ where m_x and E_x are the mass and energy of the particles, σ is the reported cross section[3] for $e + H^- \rightarrow H + 2e$ (note that the projectile and target are different than in reaction of interest) and n_e is the electron density. It can be estimated that the plasma density of the novel source is on the order of 10^{12} cm^{-3} and the temperature of the main part of the electron population on the order of 3-10 eV (with a significant tail to high energies similar to the LANSCE filament source[4]). The resulting calculation yields that in the case of the ECR-driven

source almost 90 % of the H^- ions should survive as they travel through the plasma (d = 90 mm). This fraction is estimated to be similar for the filament- and helicon-driven sources.

(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. 3 it can be calculated that the H^- losses in this pressure range are less than 10% within a propagated distance of < 10 cm. The ability to reduce the neutral gas pressure from 5-10 mTorr (corresponding to H^- losses of tens of percent), which is typical for the LANSCE helicon source, producing 12 -13 mA of H^-, is the greatest motivation for the novel source design.

(3) $H^- + Cs^0 \rightarrow H^0$: The calculation for H^- losses in collisions with neutral cesium atoms (based on the reported cross section[5]) 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.

Based on these considerations we estimate that > 70 % of the H- formed on the converter surface of the ECR-driven source could survive through the plasma to the outlet.

Brief Discussion on Beam Formation

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 (filament sources). The trajectories of the H^- ions are affected by the magnetic field in the region between the converter and the outlet aperture. In contrast to the helicon source, for which the magnetic field has to be a compromise between optimized coupling of rf-power (maximum plasma density) and beam propagation, the magnetic field of the ECR-driven ion source can be optimized for both functions simultaneously.

CONCEPTUAL DESIGN OF THE ECR SURFACE CONVERSION ION SOURCE

The main design objectives of the new ion source concept were high ionization efficiency (low neutral gas pressure) and compactness. Therefore, an ionization mechanism relying on a resonant process, i.e. electron cyclotron wave – plasma interaction, was an obvious choice. Negative ion sources (for H^-) based on ECR plasma heating have been designed and built earlier. The approach of Tuske *et al.*[6] has been to separate the main plasma from the H^- production region by a filter magnetic field reducing the electron temperature and, consequently, stripping losses of (slow) negative ions near the outlet aperture. H^- ion beam currents on the order of 5 mA have been obtained with that source type. The main drawback of this approach is the drop of plasma density, imposed by the filter field, between the two stages of the source. This limitation can be overcome with a converter-type ion source. Takagi *et al.*[7] have designed and tested an ECR-driven plasma sputter ion source equipped with a converter electrode. In that source the converter electrode was used also as an antenna coupling the microwave power with the plasma. Negative ion beam currents of 7 mA have been obtained with the source[7]. 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 the problems encountered with this source design we used MicroWave Studio[8] 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 Ref. 7 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. The microwave-driven ion source design presented in this article has some similarities with the source described in Ref. 7. In order to optimize the ionization process we designed the plasma chamber to be a resonant cavity for TE_{111} eigenmode at 2.45 GHz, which should significantly improve the coupling efficiency of the microwaves. Variation of this design is used at CERN (ISOLDE) for ionization of noble gas radioisotopes (positive ions)[9].

A schematic drawing of the 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.

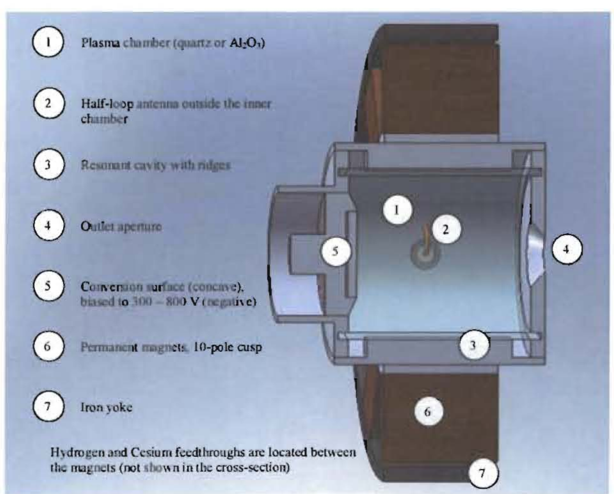

FIGURE 1. A schematic of the proposed ECR-driven surface conversion ion source.

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. MicroWave Studio (MWS eigensolver) was used to design the resonant cavity. 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 are listed in Table 1.

TABLE 1. RF-cavity dimensions

Parameter	Value[mm]	Comment
Cavity inner radius, r_{cav}	45	
Cavity length, L_{cav}	80	
Quartz-tube outer radius, r_{out}	37.5	
Quartz-tube wall thickness, r_t	3.175	
Ridge width	20	
Ridge height	r_{cav} - r_{out}	Fills the space between the cavity and inner chamber
Ridge-end-wall gap length	8	

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.

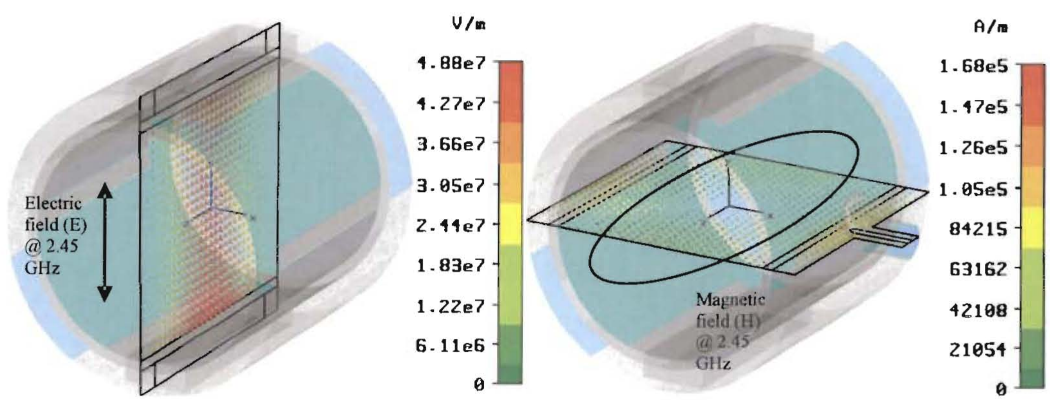

FIGURE 2. Electric field (left) and magnetic field (right) of the TE_{111} eigenmode (at 2.45 GHz) excited in the cavity of the proposed ECR-driven surface conversion ion source.

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.

The electrons in the plasma are accelerated in a resonance when their Larmor frequency in the external magnetic field equals to the microwave frequency. These energetic electrons ionize neutral atoms and maintain the plasma. 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. 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 radially. The Figure also shows that the strength of the magnetic field falls to zero on the source axis.

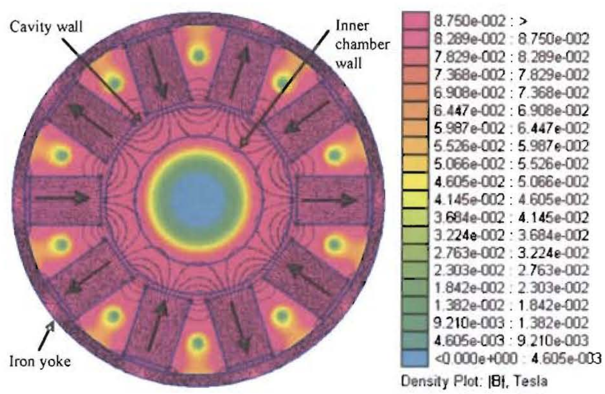

FIGURE 3. The cusp magnetic field and corresponding resonance surface of the proposed ECR-driven surface conversion ion source. Simulation with FEMM[10].

The magnetic field being zero on the source axis 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 axis (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[11]. 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. Reducing the number of magnetic poles would make 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. Also the magnet length affects the size of the beam spot at the outlet aperture. 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.

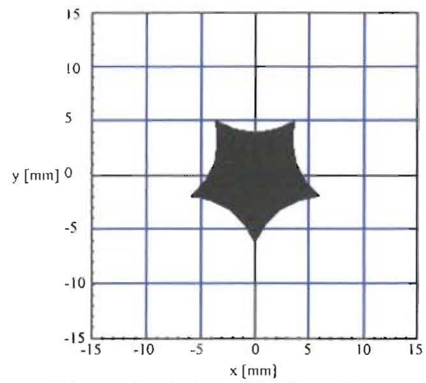

FIGURE 4. The results of the ion tracking calculation. The "star" represents the predicted beam spot at the outlet aperture.

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. If the thickness of the conductive layer exceeds the skin depth of 2.45 GHz microwaves, the coupling of the power to the electrons is prevented (strictly speaking, the field amplitude falls to 1/e from the original). The skin depth δ depends on the electrical conductivity of the metal. This process can be affected 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. Our simulations have demonstrated that with a proper design the shielding does not affect the mode structure.

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 %.

The source design 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 (such as xenon or cesium) induced sputtering of the cesiated surface will result into emission of negative ions. In addition the source concept could be used for the production of intense proton ion beams. Ion beam (H^+) currents of >100 mA have been produced with 2.45 GHz ECR ion sources[12].

ACKNOWLEDGMENTS

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