Analysis of the H^- Extraction in the Linac4 Negative Ion Source by 2.5D Particle Simulation

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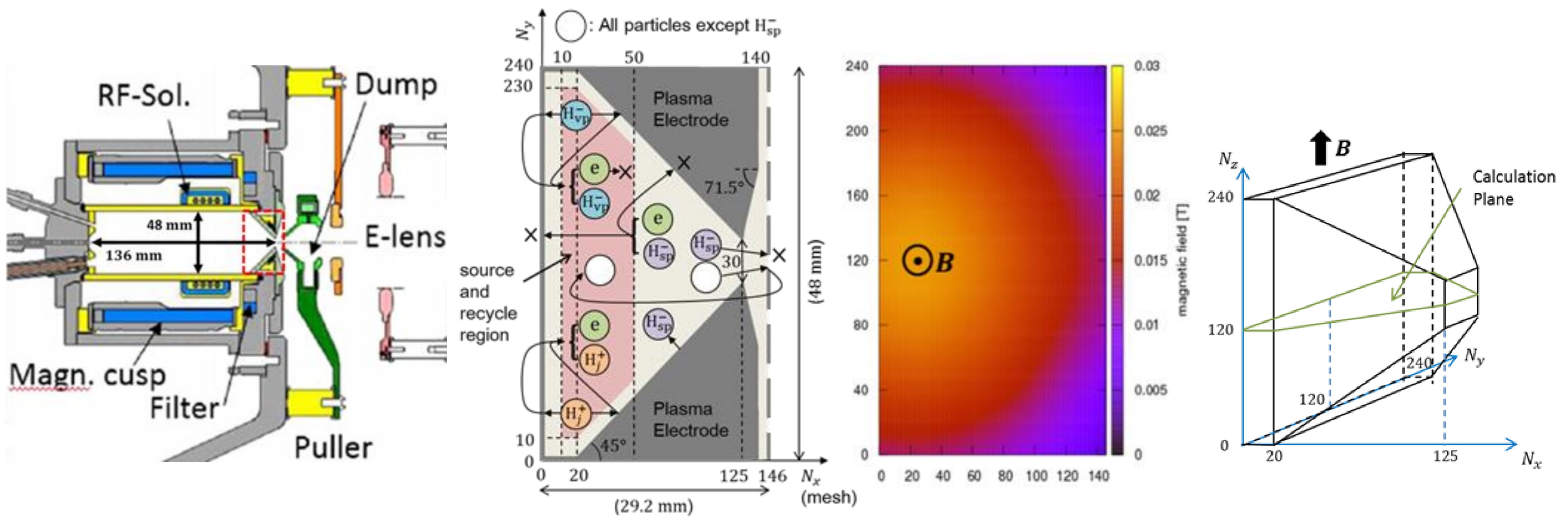
ABSTRACT

Linac4 cesiated surface negative ion source is required to produce 50 mA of H- ions within a normalized rms emittance of 0.25π mm·mrad [1-2]. In order to achieve the requirements, it is necessary to understand the mechanisms of the H^- beam extraction and optimize the process. Recently, the effects of the operation parameters (e.g. magnetic filter and plasma electrode shape) on the H^-extraction have been investigated by the simulations [4] and the experiments [1-3]. However, the optimization methods have not been completely analyzed. Therefore, the purpose of this study is to analyze the mechanisms of the H^-extraction, and to investigate the effects of the operation parameters on the H^-beam current and divergence in the Linac4 negative ion source by using the 2D-PIC model. 2D models are useful to understand the basic physics of the H^-extraction [5-7] and are suitable for a wide range of the parameter surveys of the operation parameters. In this study, the mechanisms of the H^- transport and extraction are investigated for the first step to validate the model and to take important effects into account for a reasonable parameter survey. We have analyzed the beam divergence in the volume case and the effects of the following collisions on the H^- extraction have been analyzed in the surface case; elastic (H^-_{sp} - H_2) and charge exchange (H^-_{sp} - H). In the volume case, the typical tendency between the beam divergence and the extraction voltage has been obtained. The results show that the beam divergence depends on the shape of the plasma meniscus. In the surface case, the H^-_{sp} current has increased and the H^-_{sp} divergence has decreased due to the collisions. This is because the flow reversal at the deep positon was caused by the collisions. in the Linac4 negative ion source, the flow reversal of the H^-_{sp} ions due to the collisions of H^-_{sp} - H and - H2 possibly becomes one of the important mechanisms of the H− extraction.

SIMULATION MODEL



- The motion of the charged particles (electrons, volume and surface produced H^- (H^-_{vp} and H^-_{sp}) ions, H^+ ions, H_2^+ ions and H_3^+ ions) is solved by PIC method.
- The reduced size scaling method [6-8] is used with the scaling factor $s = 2.63 \times 10^{-2}$. Therefore, the mesh interval corresponds to $0.5\lambda_{De}$, where λ_{De} is electron Debye length ($\lambda_{De} = 1.05 \times 10^{-5}$ m).
- The extraction voltage ϕ_{ext} and the magnetic filter field are specified based on the experimental data [10]. These fields are uniform in the z direction.
- In order to take into account the particle loss in the z direction, which is an important effect [8], there are boundaries in the z direction. When the negatively charged particles reach these boundaries, the reflection effect due to the sheath potential is also taken into account.
- The collisions listed in TABLE 1 have been introduced by the Null Collision Method [11] under the assumption that there is a uniform neutral gas background with the constant densities and temperatures.

- In this study, three cases (Volume source, Surface source case1 and Surface source case2) shown in TABLE 1 have been calculated.
  - In each case, the mechanisms of the H- extraction has mainly been focused.
  - In the surface source, the effects of the collisions listed in TABLE 1 on the H- extraction have been analyzed.
- The simulations have been calculated under the conditions shown in tables [4,9,10] with the time step $\Delta t = 0.4/\omega_{pe}$, where ω_{pe} is plasma frequency ($\omega_{pe} = 5.65 \times 10^{10}$ rad/s).

TABLE 1. Particles which can experience the collisions and the collision species.

Particle	Reaction	Formula	Volume	Surface: Case1	Surface: Case2
Electron	Elastic	$e + H_2 \rightarrow e + H_2$	Yes	Yes	Yes
Electron	Elastic	$e + H \rightarrow e + H$	Yes	Yes	Yes
H^-_{sp}	Associative Detachment	$H^- + H \rightarrow H_2 + e$	-	Yes	Yes
H^-_{sp}	Elastic	$H^- + H_2 \rightarrow H^- + H_2$	-	No	Yes
H^-_{sp}	Charge Exchange (CX)	$H^- + H \rightarrow H + H^-$	-	No	Yes

TABLE 2. Initial values of the main physical parameters in the source region.

Physical Parameters	Symbol	Value
Electron Temperature	T_e	2 eV
H_j^+ (j = 1,2,3) Temperature	$T_{H_j^+}$	1.5 eV
H^-_{vp} Temperature	$T_{H^-_{vp}}$	0.25 eV
Electron Density	n_e	4×10^{18} m^{-3}
Electron and H^-_{vp} Density Ratio	$n_e : n_{H^-_{vp}}$	2 : 1
Positive Ion Density Ratio	$n_{H^+} : n_{H_2^+} : n_{H_3^+}$	10 : 1 : 2.5

TABLE 3. Parameters of the back ground gas and the H^-_{sp} ions.

Physical Parameters	Symbol	Value
H_2 Temperature	T_{H_2}	0.1 eV
H Temperature	T_H	0.75 eV
H_2 Density	n_{H_2}	6.17×10^{20} m^{-3}
H Density	n_H	1.57×10^{20} m^{-3}
H^-_{sp} Tmperature	$T_{H^-_{sp}}$	0.75 eV
H^-_{sp} Emission Rate	j_b	1000 Am^{-2}

RESULTS

Volume Source

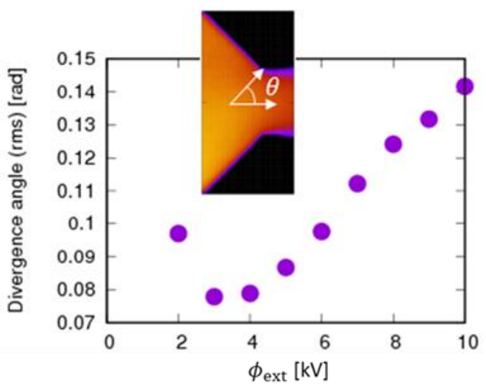


Figure 1. H^- beam divergence as a function of the extraction voltage.

The tendency of the curve with a minimum value which is the typical tendency obtained in the experiments has been obtained.

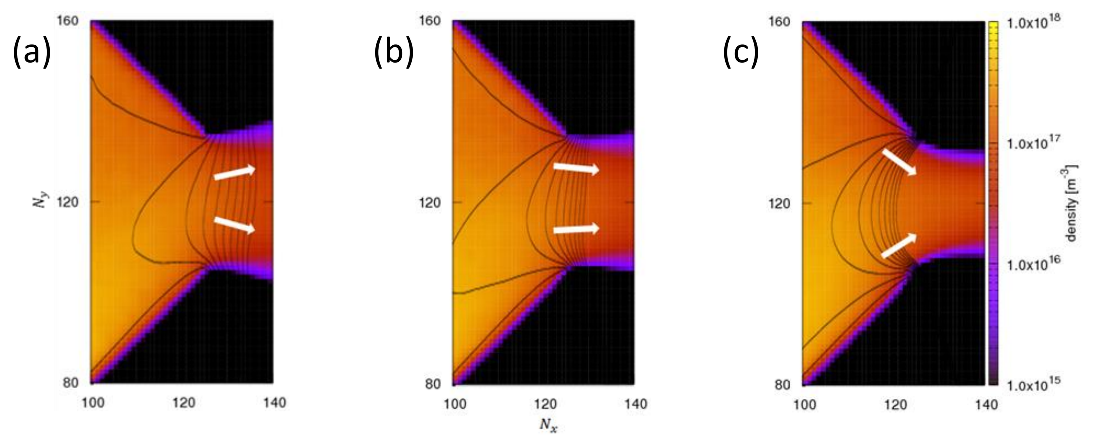


Figure 2. H^- density profile in the case of ϕ_{ext} = (a) 2 kV, (b) 4 kV, (c) 10 kV. Black lines are the equipotential lines.

- ϕ_{ext} = 2 kV case
H^- beam is diverging. As the extraction voltage is low, the plasma can be leaked from the aperture. This makes the extraction surface convex and causes beam to diverge.

- ϕ_{ext} = 4 kV case
H^- beam is extracted straightly because the equipotential lines in the vicinity of the aperture are flat.

- ϕ_{ext} = 10 kV case
H^- beam is over-focusing. This is because the extraction surface is concave due to the penetration of the extraction potential.

Surface Source

As seen in Fig. 3, each total H^- current is 20~25 mA and the e/H^- ratio is 2~6 in the both cases. In the typical experiments, the H^- current is 40 mA and the e/H^- ratio is 2~5 [1-3]. Therefore, the results agree qualitatively well with the experiments.

However, there are some differences between case1 and case2.

- The H^-_{sp} current in case2 has become larger than that in case1.
- The divergence angle of the H^-_{sp} ions has become smaller in case2 while the divergence of the H^-_{vp} ions is almost unchanged.

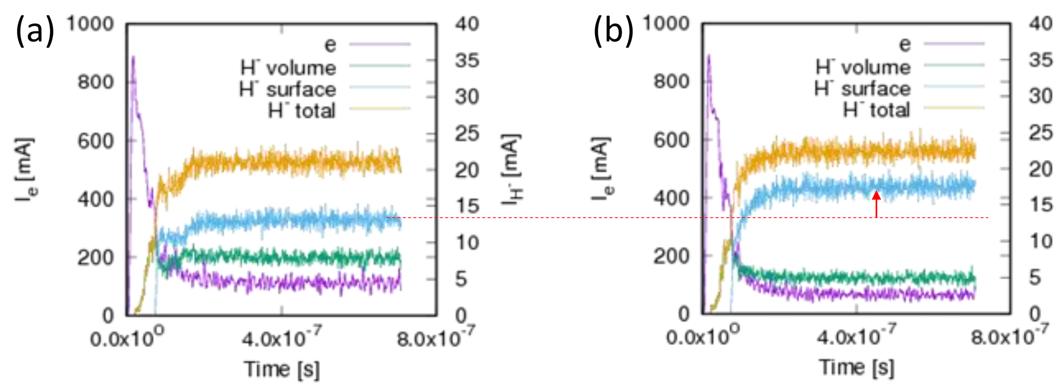


Figure 3. Electron and H^- current in (a) case1 and (b) case2.

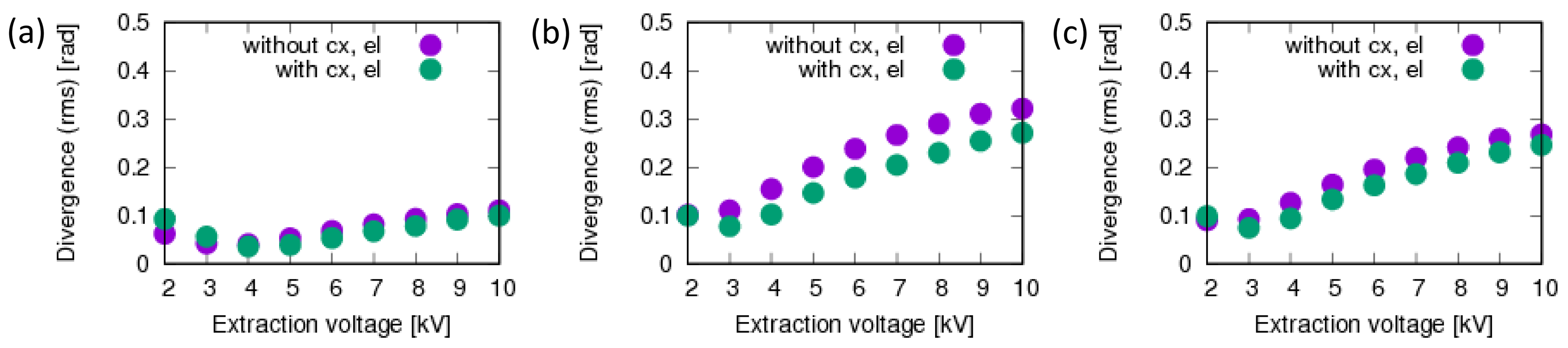


Figure 4. Ion beam divergence angle as a function of the extraction voltage; (a) H^-_{vp} ions, (b) H^-_{sp} ions and (c) all the H^- ions.

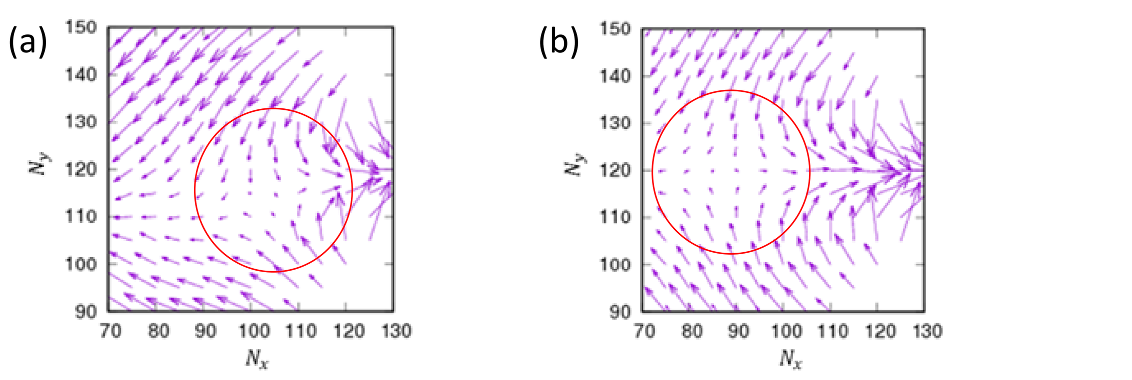


Figure 5. Flow of the surface produced H^- ions in the (a) case1 and (b) case2.

As seen in Fig. 5, the flow reversal of the H^-_{sp} ions occurs at deeper position in case 2 than that in case1 due to the collisions of Elastic and CX.

Increase of the H^-_{sp} current

The H^-_{sp} ions produced away from the aperture whose velocity is relaxed can be extracted.

The amount of the non-divergence (core) component in the extracted H^-_{sp} ions becomes larger.

Decrease of the divergence angle of the H^-_{sp} ions

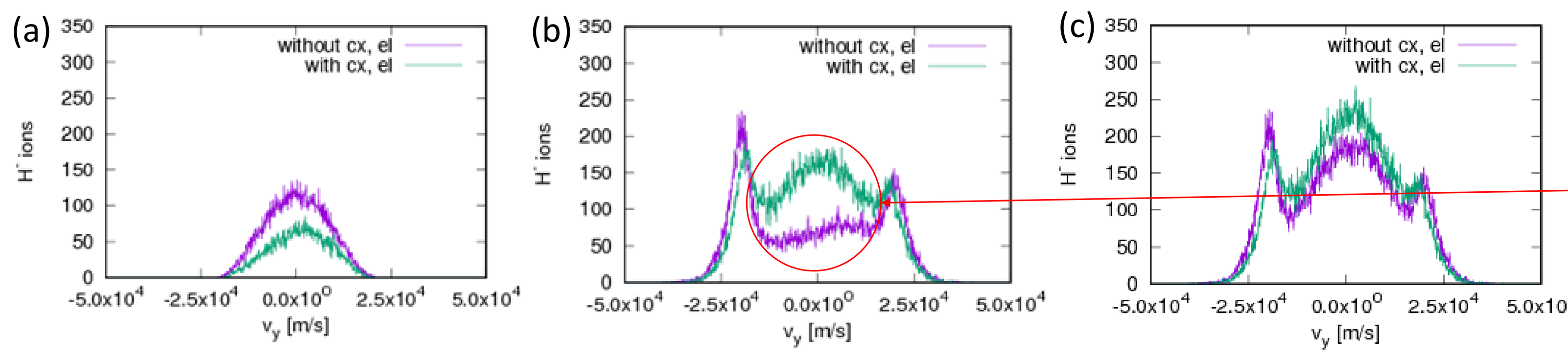


Figure 6. Ion Velocity Distribution Function (IVDF) for the vertical component to the extraction axis at the extraction surface (plasma meniscus); (a) H^-_{vp} ions, (b) H^-_{sp} ions and (c) all the H^- ions.

CONCLUSION

- In the volume case, the H^- beam divergence is shown as the function of the extraction voltage and the tendency is the curve with a minimum value. This is because both the low and high extraction voltage contribute to the curve of the extraction surface which causes divergence component of the H^- beam.
- In the surface case, the effects of the collisions between H^-_{sp} - H and H^-_{sp} - H_2 on the H^- extraction in the Linac4 negative ion source have been analyzed.
  - The extracted H^-_{sp} current is larger in the collisional case because these collisions cause the flow reversal of the H^-_{sp} at the deep position in the extraction region.
  - the divergence angle of the H^-_{sp} ions has become smaller in the collisional case due to the increase of the non-divergence (core) component in the extracted H^-_{sp} ions by the flow reversal.
- We will continue to analyze the mechanisms of the H^- extraction in the Linac4 negative ion source and investigate the effects of the operation parameters on the H^- extraction based on such analysis in the future.

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