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Title: Integrated Modeling of the Beam Formation and Extraction in the Linac4 Hydrogen Negative Ion Source

Year: 2018

Version: Published version

Please cite the original version:

Nishioka, S., Abe, S., Mattei, S., Lallement, J. B., Kalvas, T., Hatayama, A., & Lettry, J. (2018). Integrated Modeling of the Beam Formation and Extraction in the Linac4 Hydrogen Negative Ion Source. In J. Lettry, E. Mahner, B. Marsh, R. Pardo, & R. Scrivens (Eds.), Proceedings of the 17th International Conference on Ion Sources (Article 080017). AIP Publishing. AIP Conference Proceedings, 2011. https://doi.org/10.1063/1.5053372

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Citation: AIP Conference Proceedings **2011**, 080017 (2018); doi: 10.1063/1.5053372
View online: https://doi.org/10.1063/1.5053372
View Table of Contents: http://aip.scitation.org/toc/apc/2011/1
Published by the American Institute of Physics

Integrated Modeling of the Beam Formation and Extraction in the Linac4 Hydrogen Negative Ion Source

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Abstract.
In order to make the predictive simulation tools for the extracted beam current and emittance in the Linac4 H^- ion source, we have launched the development of the integrated model for the H^- ion beam formation and extraction process. More specifically, our 3D KEIO-Beam Formation and eXtraction (3D KEIO-BFX) is coupled with the NINJA, IBSIMU and TRAVEL. The extracted H^- ion beam current and co-extracted electron current obtained by the integrated model have shown reasonable agreement with the experiments.

INTRODUCTION

Linac4 H^- ion source is required to deliver 50 mA of H^- ion beam within a transverse rms emittance of 0.25π mm·mrad[1]. In order to demonstrate the feasibility of these requirements, it is indispensable to study the H^- beam formation and extraction processes in the vicinity of the beam extraction hole (extraction region). Recently, the effects of the operation parameters on the H^- beam formation and extraction have been investigated by a 2D Particle in Cell (PIC) model[2] and a 3D PIC model[3]. In Ref. 2, it has been shown that the 2D PIC code is useful to understand the basic physics of the H^- extraction in the qualitative sense.

In order to make a more predictive PIC model for the H^- beam formation and extraction in the quantitative sense, we have launched the development of the integrated model for the beam formation and extraction. More specifically, our 3D PIC model for the extraction region, i.e. KEIO-Beam Formation and eXtraction (KEIO-BFX)[4], is coupled with the NINJA[5] for the source plasma calculation, IBSIMU[6] for the beam transport in the acceleration region, and the TRAVEL[7] for the beam transport in the Low Energy Beam Transport (LEBT) region. The purpose of the present study is to report the first results by the integrated model for the beam formation and extraction process. The obtained extracted beam current and beam emittance in the case of the H^- ion extraction without the cesium will be shown.

INTEGRATED MODEL FOR THE BEAM FORMATION AND EXTRACTION

The integrated model in the present study consists of the coupling of NINJA[5], KEIO-BFX[4], IBSIMU[6] and TRAVEL[7]. The detailed description for each code can be found in the corresponding references.

In the present integrated model, the extraction region in the Linac4 H^- ion source is modeled by the 3D KEIO-BFX. The 3D KEIO-BFX solves the motion of the charged particles (electrons, volume produced H^- ions (H^-_{vp}), H^+ ions, H_2^+ ions and H_3^+ ions) and the electric field self-consistently by the 3D PIC method. FIGURE 1 shows the

Proceedings of the 17th International Conference on Ion Sources
AIP Conf. Proc. 2011, 080017-1–080017-3; https://doi.org/10.1063/1.5053372
Published by AIP Publishing. 978-0-7354-1727-4/$30.00

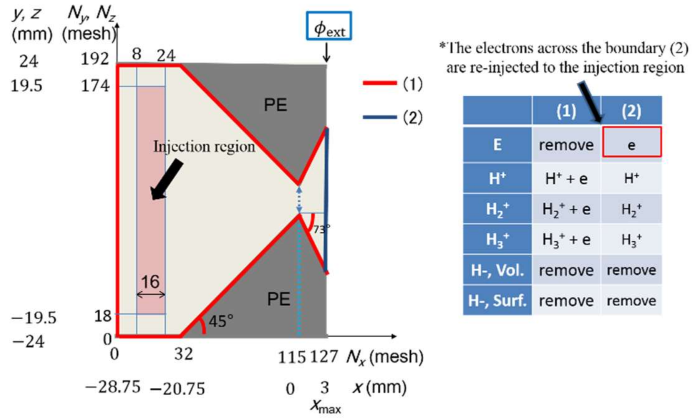

FIGURE 1. Schematic viewgraph of the integrated model for the beam formation and extraction. The table shows the boundary conditions for each particles e.g. H^+ ions across the boundary (1) are re-injected into the injection region with the electrons at exact same position.

schematic view of the simulation model. In this model, the reduced size scaling method[5] has been used with the scaling factor $s = 1.8 \times 10^{-2}$. Therefore, the mesh interval corresponds to $0.625\lambda_{\mathrm{De}}$, where λ_{De} is electron Debye length ($\lambda_{\mathrm{De}} = 7.1 \times 10^{-6}$ m).

The potential at the Plasma Electrode (PE) and the other boundaries (except for the $x = x_{max}$) are set to 0 V. The extraction voltage at $x = x_{max}$ is specified based on the IBSIMU result with the voltage of 10 kV. The full 3D magnetic filter field structure in the extraction region is specified from the experimental data[8].

The input physical parameters in the 3D KEIO-BFX are summarized in Table 1. All of these parameters are based on the NINJA results at the injection region in the case of the following operation parameters: 40 kW RF power, 2 MHz RF frequency and 3 Pa gas pressure.

In the KEIO-BFX code, the H^- volume production and loss reactions, as listed in TABLE 2, have been introduced by Null Collision Method[9] under the assumption of the uniform neutral gas background with the constant densities and temperatures; $\sum_{v=0}^{13} n_{\mathrm{H_2}}(v) = 6.17 \times 10^{20}\ \mathrm{m^{-3}}$, where the v is the vibrational excited state, $n_{\mathrm{H}} = 1.57 \times 10^{20}\ \mathrm{m^{-3}}$, $T_{\mathrm{H_2}} = 0.1$ eV and $T_{\mathrm{H}} = 0.75$ eV. It should be noted that the hydrogen molecule density for each vibrational excited state has been taken into account based on the results from NINJA. The simulations time step is $\Delta t = 0.4/\omega_{\mathrm{pe}}$, where ω_{pe} is plasma frequency ($\omega_{\mathrm{pe}} = 1.8 \times 10^{10}$ rad/s).

In the beam formation and extraction calculations by 3D KEIO-BFX code, some of the particles are extracted from the boundary at $x = x_{max}$. All these extracted particles are loaded at corresponding position in the IBSIMU code with the same velocity, the beam transport until the entrance of the LEBT is then calculated by IBSIMU itself. Finally the beam transport in the LEBT is calculated by the TRAVEL code. Based on this integrated model, the extracted H^- beam current, co-extracted electron current and the beam emittance obtained by the 3D-KEIO-BFX will be shown in the next section.

TABLE 1. Main physical input parameters.

Physical Parameters	Symbol	Value
Temperature for *j*-th species	T_j	$T_{\mathrm{H^+}} = 3.6$eV, $T_{\mathrm{H^+}} = 2.0$ eV, $T_{\mathrm{H_2^+}} = 1.8$ eV, $T_{\mathrm{H_3^+}} = 1.6$ eV
Electron Density	n_e	$4 \times 10^{18}\ \mathrm{m^{-3}}$
Ratio for each particle density	$n_e : n_{\mathrm{H^+}} : n_{\mathrm{H_2^+}} : n_{\mathrm{H_3^+}}$	40:30:3:7

TABLE 2. The collision species.

Reaction	Formula
Dissociative electron attachment (DA)	$\mathrm{e} + \mathrm{H_2}(v) \rightarrow \mathrm{H^-} + \mathrm{H}$
Associative electron detachment (AD)	$\mathrm{H^-} + \mathrm{H(1s)} \rightarrow \mathrm{H_2} + \mathrm{e}$
Associative electron detachment (AD)	$\mathrm{H^-} + \mathrm{H(1s)} \rightarrow \mathrm{e} + \mathrm{H(1s)} + \mathrm{H(1s)}$
Electron Detachment	$\mathrm{H^-} + \mathrm{e} \rightarrow \mathrm{e} + \mathrm{H} + \mathrm{e}$
H2 electron detachment	$\mathrm{H^-} + \mathrm{H_2}(v) \rightarrow \mathrm{H} + \mathrm{H_2}(v') + \mathrm{e}$

RESULTS

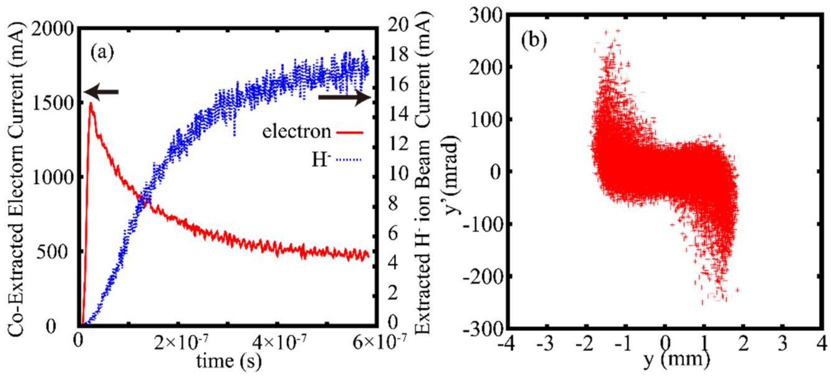

FIGURE 2. Results by the integrated model (a) time evolution of the extracted H^- ion beam current and co-extracted electron current (b) emittance diagram for the H^- ion beam at $x = x_{max}$ along the y axis.

FIGURE 2 (a) shows the time evolution of the extracted H^- ion beam current ($j_{\mathrm{H^-,ext}}$) and co-extracted electron current ($j_{e,\mathrm{ext}}$). The blue and red line show the $j_{\mathrm{H^-,ext}}$ and $j_{\mathrm{e,ext}}$. From Fig. 2(a), $j_{\mathrm{H^-,ext}}$ and $j_{e,\mathrm{ext}}/j_{\mathrm{H^-,ext}}$ are estimated to be 17.2 mA and 28.5, respectively. In the experiments[10], it was found $j_{\mathrm{H^-,ext}} =$ 20~30 mA with $j_{e,\mathrm{ext}}/j_{\mathrm{H^-,ext}} =$20~30. Therefore, $j_{\mathrm{H^-,ext}}$ and $j_{e,\mathrm{ext}}/j_{\mathrm{H^-,ext}}$ calculated by present integrated model have shown a reasonable agreement with experiments.

FIGURE 2 (b) shows the emittance diagram at the $x = x_{max}$ along the y axis which is parallel to the magnetic filter field. From Fig. 2(b), the normalized rms emittance, $\varepsilon_{\mathrm{norm,rms}}$ is estimated to be 0.08 π mm·mrad. This emittance data will be transferred to the IBSIMU code and TRAVEL-3D code, the beam transport and emittance growth in the acceleration region and the LEBT will be analyzed in the near future.

CONCLUSION

In the present study, we have developed the integrated model for the beam formation and extraction processes. The volume production case without Cs has been analyzed by the integrated model. The results of $j_{\mathrm{H^-,ext}}$ and $j_{e,\mathrm{ext}}/j_{\mathrm{H^-,ext}}$ by the integrated model have shown a reasonable agreement with the experiments. Based on the obtained results for the beam emittance, the beam transport and emittance growth in the acceleration region and LEBT will be analyzed by the IBSIMU and TRAVEL codes.

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