# IMPLEMENTATION OF H$^-$ INTRABEAM STRIPPING INTO TRACK*

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## *Abstract*

H$^-$ intrabeam stripping has been presented in Reference [1] as potentially harmful to MW scale H$^-$ linacs. If not taken properly into account, intrabeam stripping of the H$^-$ beam could lead to losses in excess of the 1 W/m limit and result in non-tolerable beamline elements activation. This paper describes the implementation of the H$^-$ intrabeam stripping effect into the beam dynamics code TRACK [2]. Simulation results and numerical applications are presented for the FNAL 3 GeV CW linac, the FNAL 8 GeV Pulsed linac and for the SNS 1 GeV linac.

## INTRODUCTION

H$^-$ ions have two electrons, one tightly bound with a binding energy of 13.6 eV and another one slightly bound at 0.75 eV of binding energy. During the acceleration and transport of the H$^-$ beam, the ions suffer from (i) black-body radiation stripping, (ii) magnetic field stripping, (iii) residual gas stripping and (iv) intrabeam stripping by H$^-$ of the same beam. All these effects can strip the slightly bound electron and result in the loss of the neutral hydrogen atom.

Stripping effects (i)-(iii) have been implemented into the beam dynamics code `TRACK` as reported in Reference [3]. This paper describes the implementation of the intrabeam stripping equations in this code. We also present the results of numerical simulations of intrabeam stripping losses along three linacs: the current FNAL SC 3 GeV CW linac, the previous FNAL SC 8 GeV Pulsed linac and the SNS linac currently being operated at ORNL.

## INTRABEAM STRIPPING THEORY

The beam fraction lost per unit length due to intrabeam stripping is presented in Reference [1] and defined by the relation:

$$\frac{1}{L} = \frac{N\sigma_H\sqrt{\gamma^2\theta_x^2+\gamma^2\theta_y^2+\theta_s^2}}{8\pi^2\sigma_x\sigma_y\sigma_s\gamma^2}F(\gamma\theta_x,\gamma\theta_y,\theta_s) \qquad (1)$$

with

- N the number of particles per RF bucket.
- $\sigma_{x,y}$ and $\sigma_s$ respectively the RMS transverse and longitudinal bunch sizes
- $\theta_{x,y}$ the local transverse RMS angular spreads defined by

$$\theta_{x,y} = \sqrt{\frac{\epsilon_{x,y}}{\beta_{x,y}\cdot\beta\gamma}} \qquad (2)$$

  with $\epsilon_{x,y}$ being the RMS normalized transverse emittance, $\beta_{x,y}$ the transverse beta funtion and $\beta\gamma$ the Lorentz factor.
- $\theta_s$ the local RMS momentum spread defined by:

$$\theta_s = \sqrt{\frac{\epsilon_s}{\beta_s\cdot\beta\gamma}} \qquad (3)$$

  with $\epsilon_s$ being the RMS normalized longitudinal emittance in [m-rad] and $\beta_s$ the longitudinal beta funtion in [m/($\Delta P/P$)]
- The function $F$ approximated by:

$$F(\theta_x,\theta_y,\theta_s) \simeq 1+\frac{2-\sqrt{3}}{\sqrt{3}(\sqrt{3}-1)}\left(\frac{\theta_x+\theta_y+\theta_s}{\sqrt{\theta_x^2+\theta_y^2+\theta_s^2}}-1\right) \qquad (4)$$

- $\sigma_H$ the intrabeam stripping cross section as defined by

$$\sigma_H(v) = \frac{240\alpha_{FS}^2a_0^2}{(v+\alpha_{FS})^2}\frac{(v-\beta_m)^6}{(v-\beta_m)^6+\beta_m^6}\ln\left(1.79\frac{v+\alpha_{FS}}{\alpha_{FS}}\right) \qquad (5)$$

  where $a_0 \simeq 52.9177\times10^{-12}$ m is the Bohr radius, $\alpha_{FS}\simeq 1/137$ the fine structure constant, $v$ the relative velocity of the H$^-$ions and $\beta_m \simeq 7.5\times10^{-5}$ the velocity where the cross-section approaches zero due to ion repulsion. The equation is justified for $\beta > \beta_m$. The relative velocity $v$ being defined by:

$$v = \beta\sqrt{(\gamma\theta_x)^2+(\gamma\theta_x)^2+\theta_s^2} \qquad (6)$$

## IMPLEMENTATION IN `TRACK`

The beam dynamics code `TRACK` developed by Argonne National Laboratory integrates the equations of motion using a fourth-order Runge-Kutta method, with a variable integration size defined for each element along the beam line. `TRACK` is a fully 3D code (3D external electric and magnetic fields and 3D space charge). Stripping losses from intrabeam stripping are implemented in `TRACK` through Eq. 1. At each integration step, the code calculates a stripping probability for every macroparticle and compares this probability with a uniformly generated random number between 0 and 1. In the event the random number is smaller than the calculated probability, the particle will be stripped. For the

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moment, stripped particles are considered lost at the location of stripping without further tracking. In the future, it is our goal to transport the neutral hydrogen in the code in order to have a better picture of the location of the beam losses.

Figure 1 compares `TRACK` simulations of the stripping losses from intrabeam stripping with analytical predictions for an 8 GeV beam going through a 1 meter drift. The overall agreement is excellent and confirms the proper implementation of the intrabeam stripping into `TRACK`.

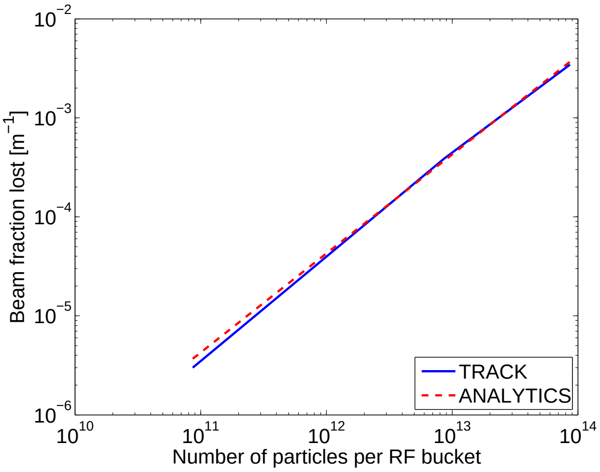

Figure 1: Comparison between `TRACK` simulation and analytical prediction of the $H^-$ beam fraction from intrabeam stripping.

## APPLICATION TO $H^-$ LINACS

Losses from intrabeam stripping were studied with `TRACK` for three high-intensity hydrogen ion linacs: the current version of the FNAL proton driver which is a SC CW linac operating at 3 GeV and designed to deliver a 3 MW average power [4], the former version of the FNAL proton driver which was an 8 GeV SC Pulsed linac [5] conceived with the primary mission of providing 2 MW proton beam at main injector energies (40-120 MeV) and finally SNS [6] in operation since 2006 at ORNL. Baseline parameters for these three accelerators are given in table 1.

Figures 2(a)-(c) show the RMS angular and momentum spread along the three linacs as calculated by `TRACK`. The corresponding intrabeam stripping losses are reported in Figure 3(a)-(c). For improved statistics, 1000 simulations

Table 1: Baseline design parameters for the FNAL CW and Pulsed linacs and the ORNL SNS linac.

| Parameter | FNAL CW | FNAL Pulsed | ORNL SNS |
|---|---|---|---|
| Energy | 3 GeV | 8 GeV | 1 GeV |
| Avg. power | 3 MW | 2 MW | 1 MW |
| Rep. rate | CW | 10 Hz | 60 Hz |
| $I_p$ from RFQ | 10 mA | 43.25 mA | 38 mA |
| $I_{av}$ per macro-pulse | 1 mA | 26 mA | 25 mA |
| $N_p$ per macro-pulse | $6.25 \times 10^{15}$ | $1.6 \times 10^{14}$ | $1.56 \times 10^{14}$ |

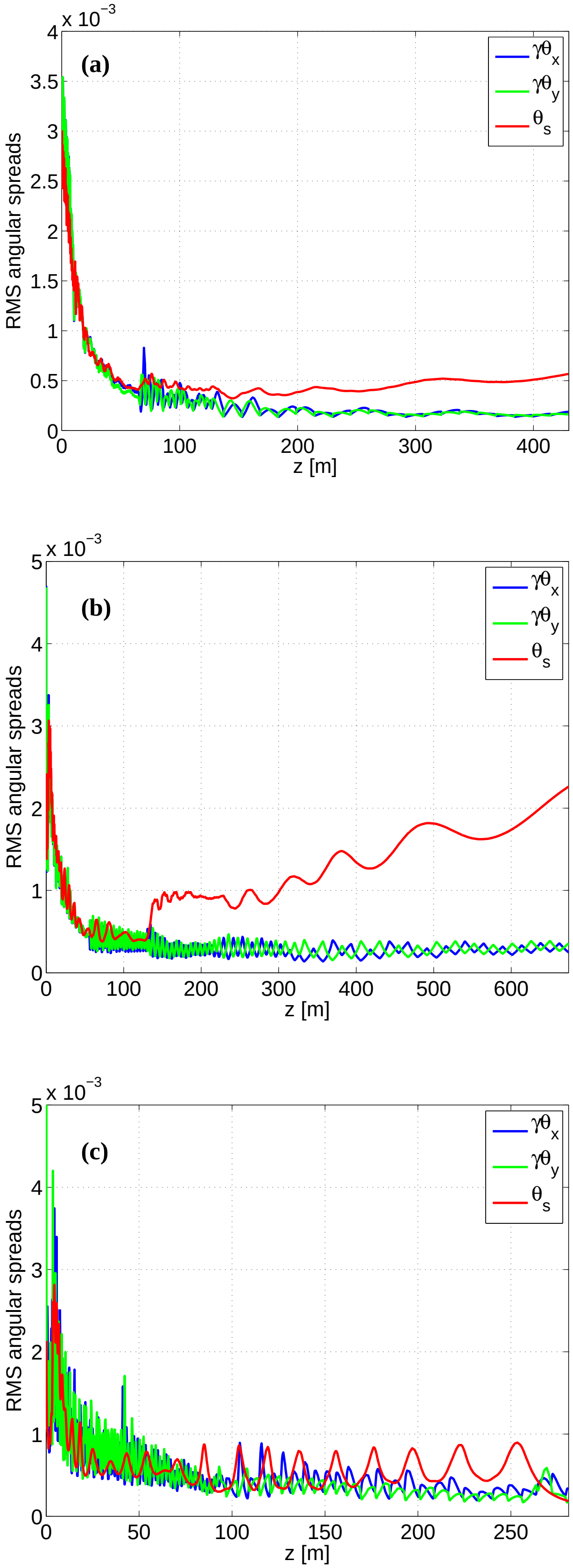

Figure 2: `TRACK` simulations of the RMS angular and momentum spreads along (a) the FNAL 3 GeV CW linac (b) the FNAL 8 GeV Pulsed linac and the (c) SNS 1 GeV linac.

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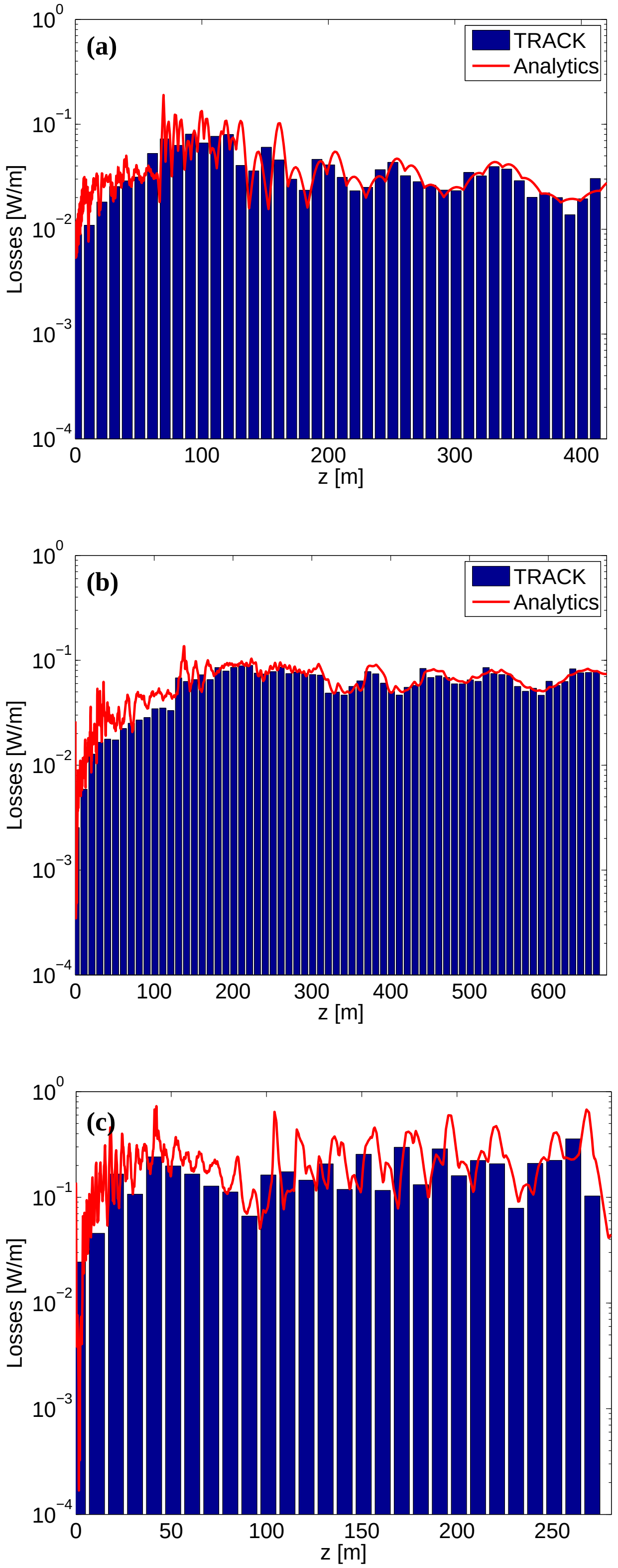

Figure 3: Comparison between `TRACK` simulations and analytical predictions (Eq. 1) of the beam power lost per meter along (a) the FNAL 3 GeV CW linac operating at 3 MW(b) the FNAL 8 GeV Pulsed linac operating at 2 MW and the (c) SNS 1 GeV linac operating at 1 MW.

were run in parallel on the FermiGrid with a different seed for the random number generator in each case. The simulations were performed with $10^6$ macroparticles per run and the losses were scaled to a beam power of 3 MW, 2 MW and 1 MW respectively for the FNAL CW, FNAL Pulsed and SNS linacs.

For the current version of the FNAL CW linac, average losses along the linac from intrabeam stripping keep below 0.1 W/m, as depicted in Figure 3(a). As a consequence, we do not consider intrabeam stripping to be a major contributor to beam losses for the current design of the FNAL linac. The same observation is made in Figure 3(b) for the previous version of the FNAL Pulsed linac operating at 2 MW. Concerning the SNS linac, losses from intrabeam stripping are more troublesome since peak losses $> 0.3$ W/m are predicted by `TRACK` as reported in Figure 3(c) for the design lattice of the SNS linac. This observation agree with the values reported in Reference [7]. Noteworthy is the good agreement between `TRACK` and the analytical prediction from Eq. 1.

## CONCLUSION

Simulations of beam losses from intrabeam stripping is now available in the code `TRACK`. Numerical simulations of the FNAL 3 GeV CW linac operating at 3 MW have shown that losses from intrabeam stripping are below $0.1$ W/m and therefore do not represent an issue for the current design of the linac. The same observation has been made for the previous design of the FNAL proton driver (8 GeV at 2 MW). Concerning the SNS linac (1 GeV at 1 MW), `TRACK` predict losses from intrabeam stripping for the baseline design of the linac to reach an uper level of $\sim 0.3$ W/m. Futher studies of intrabeam stripping losses at SNS will be made with `TRACK` including the current operating lattice in the code. Futher development of the code will also enable the tracking of the neutral hydrogen atom for a more detailed beam loss pattern.

## ACKNOWLEDGMENT

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