ION CHARGE STRIPPING FOIL MODEL FOR BEAM DYNAMICS SIMULATION*

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Abstract

An efficient computer model for the stripping foil simulation was proposed at NSCL/MSU as part of the Rare Isotope Accelerator (RIA) development. The model was successfully implemented in the LANA beam dynamics simulation code [1]. Later this model was also included in the IMPACT code [2] as well as in some other beam dynamics simulation tools [3]. The derivation of the algorithm is presented and the application of the model for the uranium beam stripping simulation in context of the RIA driver linac studies at NSCL/MSU is analyzed in the paper.

INTRODUCTION

The stripping of heavy ions is used commonly in the charged particles accelerators to boost the charge of the heavy ion and consequently the energy gain in the accelerating structure without increasing the effective accelerating voltage of the machine [4].

The negative effect from the use of the strippers on the beam is the fractional loss of intensity in the particular charge state after the stripping and 6-D phase space beam emittance increase due to multiple angular scattering and energy ionization loss straggling of the ions in the stripper material.

The first effect is minimized in the proposed RIA Driver Linac by simultaneous acceleration of several charge states [5]. The second effect – increase of the 6-D phase space emittance of the beam is taken into account in the simulation model in LANA. Other realizations of this phenomena can be found in the literature [6]. The model used in LANA for the stripper is discussed in this chapter.

PHYSICAL MODEL

The model used in LANA beam dynamics simulations is based on the simulation of multiple processes (elastic scattering, non-elastic scattering, energy loss for ionization, etc.) happening in the stripping foil.

The main effects of the heavy ion dynamics in the thin foil of condensed matter are stripping/capture of the electrons, energy loss, fluctuations of the energy loss (energy straggling), scattering on the atoms of the foil, and nuclear reactions. The scattering can be elastic and non-elastic, which contributes to the total energy loss of the particle. The present work does not include the nuclear reactions considerations, which should be the subject of a separate study. The simulation of the ion charge stripping is based on the existing research [4] and is also beyond the scope of this paper.

The main focus of this work is on the effects of the beam dynamics in the stripping foil that effects the 6-D phase space distribution of particles.

The adequate approximation of the energy straggling of the heavy ions in the stripping foil is Gaussian distribution of the probability density [7]:

$$f_E(E) = A_E \cdot e^{\frac{1}{2}\left(\frac{E-E_0}{\sigma_E^*}\right)^2} \quad , \qquad (1)$$

where E – is the final energy of the particle after passing through the foil, E_0 – is the average energy loss, σ_E^* – is the normal distribution dispersion, and A_E – is the normalization factor.

The normal distribution approximation for the probability density of the angle after multiple scattering is acceptable only for small angles [7]. For more adequate description of the tails of this distribution, which come mostly from the single or small number scattering processes, we propose to use the probability density function in the form:

$$f_\vartheta^*(\vartheta) = A_\vartheta^* \cdot e^{-\left(\frac{\vartheta}{\sigma_\vartheta}\right)^{p_\vartheta}} \quad , \qquad (2)$$

where ϑ – is the scattering angle, σ_ϑ – is the dispersion of the angular distribution, p_ϑ – is the exponential parameter of the distribution, and A_ϑ^* – is the normalization factor.

After integrating (2) in the conical layer of constant ϑ we can express the probability density of scattering in any direction at the angle ϑ as:

$$f_\vartheta(\vartheta) = A_\vartheta \cdot \sin\vartheta \cdot e^{-\left(\frac{\vartheta}{\sigma_\vartheta}\right)^{p_\vartheta}} \quad , \qquad (3)$$

where A_ϑ – is new normalization factor. For the small angles we can make an approximation in (3): $\sin\vartheta \approx \vartheta$.

Combining (1) and (3) we can write the total probability density for a single particle penetrating the stripping foil as function of two parameters, final angle and energy after passing through the foil:

$$f(\vartheta, E) = A \cdot \vartheta \cdot e^{-\left(\frac{\vartheta}{\sigma_\vartheta}\right)^{p_\vartheta}} \cdot e^{\left(\frac{E-E_0}{\sigma_E}\right)^2} \quad , \qquad (4)$$

where $A = A_E \cdot A_\vartheta$ – is total normalization factor, and $\sigma_E = \sqrt{2}\sigma_E^*$.

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Parameterization of the Stripping Foil.

The parameterization of the ion distribution after passage through the stripping foil is based on the simulation of the particle dynamics in the carbon using the code SRIM [8].

All present studies were done for the pilot beam of ^{238}U on the carbon foil in the frame of the RIA Driver Linac beam dynamics studies [9]. According to the Baron's formula [4] in the energy range of 9-12 MeV/u the equilibrium charge state after stripping in carbon foil is expected to be 73-75 with ~80% of the beam in the range ±2 charge states, and in the energy range 85-90 MeV/u the equilibrium charge state is expected to be 88-89 with ~80% of the beam in the range ±1 charge states. In our simulations we assumed the beam distributed between 71 and 75 with reference particle being 73 and between 87 and 89 with reference particle being 88 for the two given energies respectively.

Table 1 lists main particle parameters used in the SRIM simulations.

Table 1: Reference particle energy, carbon foil thickness, and its variation in SRIM calculations.

Foil #	E_{ref} [MeV/u]	T_{ref} [um]	T_{var} (±) [%]
1	12	1.78	5
2	90	64.35	5

The detailed information of the probability distributions for a single particle penetrating the stripping foil is acquired for the input particle energy range determined by the particle distribution before the foil and for the given range of the foil thickness. This probability distribution is then parameterized according to Eqs. (4), and the resulting parameters are linearly interpolated in the given ranges of the input beam energy and foil thickness.

The interpolation is done with the bilinear interpolation formula:

$$\xi = k_0 + k_E \cdot (E_{in} - E_{in0}) + k_t \cdot (t - t_0) \quad (3),$$

where: ξ is one of the parameters in Eq. (4), k_0 – the constant – value of the parameter at the reference point in SRIM simulation from the Table 1, k_E – the linear coefficient vs. input ion energy, k_t – the linear coefficient vs. foil thickness.

Tables 2 and 3 list all the parameters in Eq. (4) for the stripping foils 1 and 2 respectively derived from SRIM analysis and used in the beam dynamics simulations.

Figure 1 shows for the case of the first stripper as an example the probability density distribution of the single particle going through the stripping foil as a function of the angle and energy after the foil for three cases of the foil thickness: nominal and two cases of +5% and –5%. The difference between the SRIM simulation results and the analytic formula (4) prediction was less then 5-10% in all calculated cases.

Table 2: Analytic model parameters for stripper foil 1

Parameter	Constant	Linear coeff. vs. energy	Linear coeff. vs. thickness
σ_ϑ	0.4219 [mrad]	-0.0398 [mrad/(MeV/u)]	0.1725 [mrad/μm]
p_ϑ	1.5305	-0.0088 [1/(MeV/u)]	0.0999 [1/μm]
E_0	11.7898 [MeV/u]	1.0042	-0.1182 [(MeV/u)/ μm]
σ_E	0.002289 [MeV/u]	1.202×10^{-5}	6.99×10^{-4} [(MeV/u)/ μm]

Table 3: Analytic model parameters for stripper foil 2

Parameter	Constant	Linear coeff. vs. energy	Linear coeff. vs. thickness
σ_ϑ	0.4798 [mrad]	-0.007078 [mrad/(MeV/u)]	0.004236 [mrad/μm]
p_ϑ	1.7007	-0.00104 [1/(MeV/u)]	0.001108 [1/μm]
E_0	86.9301 [MeV/u]	1.0243	-0.04841 [(MeV/u)/ μm]
σ_E	0.01723 [MeV/u]	3.97×10^{-5}	1.8×10^{-4} [(MeV/u)/ μm]

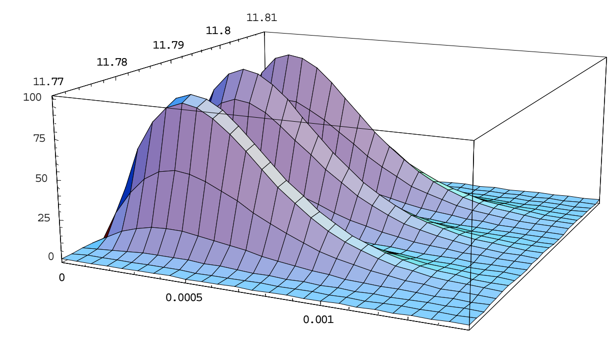

Figure 1: Probability density of the single particle scattering to the angle *x* (horizontal axis to the right) with energy after the foil *y* (horizontal axis into the paper) for the nominal foil thickness and ±5%.

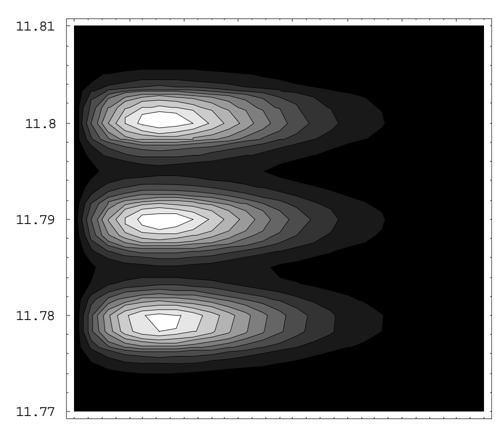

Figure 2: The contour plot of the Figure 1.

Figure 2 shows the corresponding contour plot of the function from Figure 1. Figure 2 clearly shows the same three bumps for three different thickness cases of the stripping foil. The main effect of the variation of the foil thickness is change in the average energy loss of the particle. The ensemble of particles distributed in energy penetrating the foil of varying thickness will create a smooth distribution covering the whole energy spread between the bumps shown on the Figures 1 and 2.

BEAM DYNAMICS SIMULATION RESULTS

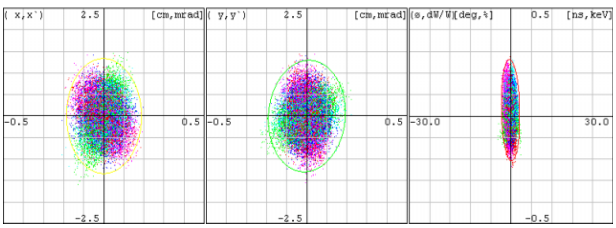

Figure 3: Phase space portraits of $^{238}U^{71-75+}$ at the charge stripping foil 2 (f_{rf}=322 MHz).

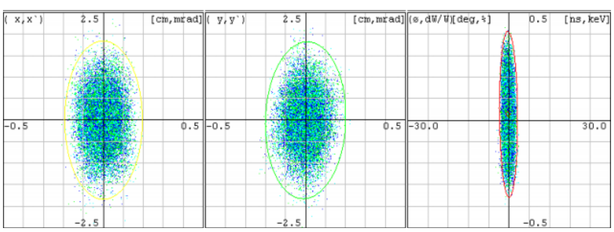

Figure 4: Phase space portraits of $^{238}U^{87-89+}$ after the charge stripping foil 2 (f_{rf}=322 MHz).

Table 4: Courant-Snyder parameters and 99.5% normalized emittances of the beam before and after the stripper foil 1 (f_{rf}=80.5 MHz) and foil 2 (f_{rf}=322 MHz).

Parameter	Foil # 1		Foil # 2	
	Before	After	Before	After
α_X	-0.065	-0.058	0.006	0.004
β_X (m)	0.680	0.633	1.401	1.056
ε_X (π mm mrad)	0.670	0.811	1.096	1.573
α_Y	-0.085	-0.080	-0.062	-0.049
β_Y (m)	0.638	0.597	1.488	1.106
ε_Y (π mm mrad)	0.648	0.768	1.093	1.613
α_Z	0.660	0.504	0.113	0.074
β_Z (°/%)	21.03	15.73	11.75	6.97
ε_Z (π KeV/u ns)	2.26	3.52	4.76	7.67

The beam particle phase space coordinates and the charge state is mapped from the particles distribution in front of the foil into the corresponding one after the foil. The charge state change is handled separately. The particular phase space coordinates transformation is given by the probability density function with the empirical formula, which is determined by fitting the numerical results from SRIM. In the beam dynamics simulations we suppose the foil to be negligibly thin so the position coordinates of the particle do not change in the foil. With this supposition only the 3-D momentum of each particle had to be changed.

Figures 3 and 4 show as an example the pilot beam phase space portraits before and after the second stripping foil simulated [9]. Table 4 lists the Courant-Snyder parameters and the emittances of the beam in the main projections of the 6-D phase space for both foils.

CONCLUSION

The algorithm developed can efficiently simulate the major effects of the stripping foil on the beam of heavy ions. The existing realizations of the proposed model are used for the research of the beam dynamics in the modern heavy ion linear accelerators. The further development of this model should include the most recent experimental data [10] on the specific energy straggling of the heavy ions in different materials. Additional studies of the contamination of the primary beam after the stripping foil with the fission fragments should be performed in order to quantify the requirements for the charge selection systems for linacs with strict loss requirements, like RIA Driver.

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