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# Macro-particle simulation of multi-species beams in CSNS/LRBT☆

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**Abstract**

At the Chinese Spallation Neutron Source (CSNS), a transverse collimation system consisting of foil scrapers and 60° triplet cells in the Linac to Ring Beam Transport line (LRBT) is designed, and the scraped particles are transported to the linac development dump. For hands-on maintenance, it is important to study the beam loss in transporting the stripped protons. Due to the lack of appropriate simulation codes to track the mixed beams, a new simulation code Stripping Collimation and Mixed Beam Transport (SCOMT) was developed to tackle the problem. The macro-particles simulation code tracks simultaneously the main $H^-$, the fully stripped proton and the partially-stripped $H^0$ beams. It also takes into account the stripping efficiency of $H^-$ in foils, nuclear absorption, nuclear elastic scattering and multiple scattering effect, etc. The SCOMT simulations were carried out at the LRBT for the design optimization. It is found that the second-time foil traverse of both the protons and the $H^0$ particles has an important contribution to the beam loss. The foil thickness has been optimized to reduce the total beam loss.

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*Keywords:* Transverse halo collimation; $H^-$ foil stripping; Transporting mixed beams; Multiple nuclear scattering; Beam loss

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## 1. Introduction

In the high-power proton accelerator with a synchrotron or an accumulator ring such as the Chinese Spallation Neutron Source (CSNS), it is important to design a transverse collimation system in the Linac to Ring Beam Transport (LRBT) (to reduce the beam losses in the ring. At the CSNS, the transverse beam halo will be collimated by using foil scrapers and periodic triplet cells of 60° in phase advance in the LRBT, and the scraped particles are transported to the linac development dump. For hands-on maintenance, it is important to study the beam loss in transporting the stripped protons. No simulation code has been found to be appropriate for the task. Some frequently used codes such as PARMILA [1], ORBIT [2] and TURTLE [3] can deal with some of the problems encountered here but not all of them.

A new simulation code Stripping Collimation and Mixed Beam Transport (SCOMT) has been developed to tackle the problems. The macro-particles simulation code tracks simultaneously the original $H^-$, the fully stripped proton and the partially stripped $H^0$ beams, and takes into account the stripping efficiency of $H^-$ in the foils, and the multiple nuclear scattering effect in the foils. It is found that at the LRBT, the energy loss of the stripped particles, the large angle nuclear elastic scattering, the nuclear absorption and the displacement caused by multiple scattering can be ignored. The code has been used in the optimization of the beam line design, and can be used on other similar applications.

## 2. Transverse collimation system in the LRBT

The layout of LRBT [4] is shown in Fig. 1. It consists of three branches: the major line to the RCS with $H^-$ beam, a straight beam dump for the initial commissioning of the

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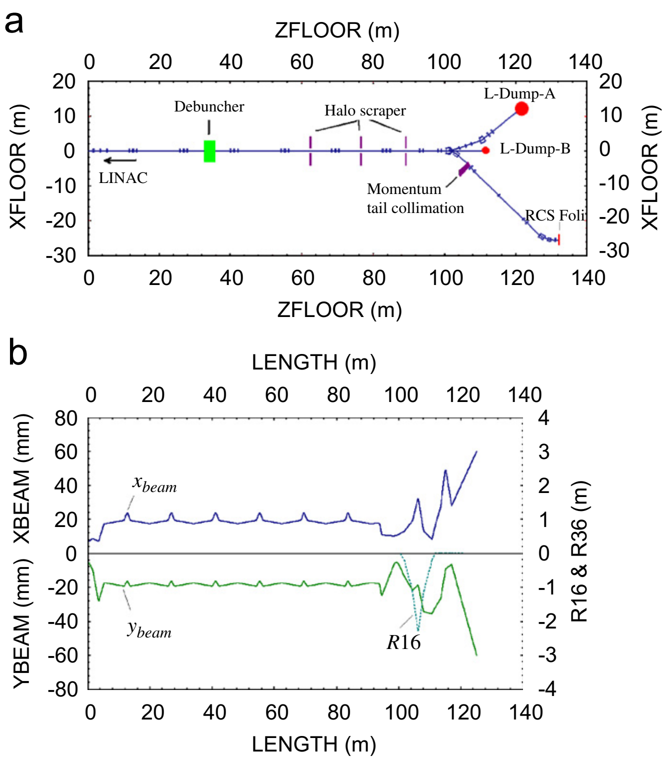

Fig. 1. The layout of LRBT (Fig. 1a) and the beam envelops from the linac to L-Dump-B (Fig. 1b).

linac and the dumping of the $H^0$ particles during normal operation, and an achromatic bending line for the full power commissioning of the linac (changing the polarity of the switch magnet) and the dumping of the stripped protons by the collimators during normal operation. The method of using three sets of foil scrapers (carbon or alumina) together with periodic triplet cells is proposed to collimate the transverse beam halo and transport the scrapped particles to the beam dumps [5]. Each set of foil scraper consists of two pairs of stripping foils with one in the horizontal plane and the other in the vertical plane. This method has the advantages of being very clean due to low beam losses in the line and low cost due to no need for additional absorption collimators or beam dumps.

During normal operation, halo particles scraped by the foils are predominantly converted into protons and a very small portion was converted into $H^0$. After the switch magnet, the three kinds of particles will separate naturally. The $H^-$ beam with a smaller emittance of a hexagonal shape in both horizontal and vertical phase planes will go to the RCS, the $H^0$ particles to Dump A and the protons to Dump B.

Although the beam line with the periodic triplet cells is perfectly matched for both the $H^-$ and proton beams, there is still beam loss due to the multiple scattering effect in the foils and the $H^0$ particles that get lost before reaching Dump A or are converted into protons with bad matching by a second time stripping. The study including all the above factors is needed to ensure low beam loss in the line, and this will be accomplished by using the simulation code SCOMT that will be further presented in the next section.

## 3. The simulation code SCOMT

As mentioned above, several functions are needed to be included in the code to simulate the transport process of the $H^-$ beam through a beam line with foil scrapers: the input distribution for the $H^-$ beam, the collimation effect in a foil scraper, the stripping efficiency of the $H^-$ beam in a foil and the charge change, the Coulomb scattering of protons in a foil, the transport of the mixed beams through the beam line elements, the beam loss registration, etc. They will be briefly explained below.

The input distribution $(x, x', y, y', p_0)$ can be either generated in the program, e.g. a truncated $2\times 2$-D or 4-D Gaussian distribution for the transverse planes, or imported from a file generated by another code. A large number of macro-particles are needed for this kind of simulation due to very low beam loss rate. All $H^-$ particles encountering a foil scraper will be marked as being collimated, and they are converted into either protons or $H^0$. A charge label is to distinguish among $H^-$, proton and $H^0$ particles.

Similar to TURTLE, the beam line elements are input by sequence, and only the linear matrices are considered. The black body apertures are included to determine the loss of particles.

The code has also the potential to include thick collimators, space charge effect and non-linear elements in the future.

### 3.1. Stripping efficiency of $H^-$ beam in a foil

When a $H^-$ particle passes through a thin foil, it can be stripped into a proton or partially stripped into a $H^0$ particle or remains as $H^-$. The $H^0$ and $H^-$ particles can be stripped in the next layers if the foil is divided into layers. The stripping probabilities of $H^-$ particles into $H^0$ particles or protons in a layer are calculated by using the following formulae:

$$\begin{aligned} \eta_{-1,0} &= 1 - e^{N\Delta t\sigma_{-1,0}} \\ \eta_{-1,1} &= 1 - e^{N\Delta t\sigma_{-1,1}} \\ \eta_{0,1} &= 1 - e^{N\Delta t\sigma_{0,1}} \end{aligned} \tag{1}$$

where $N\Delta t$ is the number of atoms per unit area in the layer; $\sigma_{-1,0} = 6.76\times 10^{-19}\,\mathrm{cm}^2$, $\sigma_{-1,1} = 0.12\times 10^{-19}\,\mathrm{cm}^2$, $\sigma_{0,1} = 2.64\times 10^{-19}\,\mathrm{cm}^2$ are the cross-sections of the conversions for $H^-$ into $H^0$, $H^-$ into proton and $H^0$ into proton through a carbon foil, which are measured at 800 MeV by Gulley et al. [6]. The energy dependence can use the simple $1/\beta^2$ scaling.