Charge Exchange Injection of Heavy Ions in Synchrotrons

D. Dinev, V. Anguelov, S. Tzenov[1]
Institute for Nuclear Research and Nuclear Energy,
72 Tsarigradsko Shaussee,1784 Sofia

V. Mikhailov
Joint Institute for Nuclear Research,Dubna,101000,Russia

Abstract

The problems of the charge exchange injection of heavy ions in synchrotrons are discussed. The equilibrium charge distributions behind the stripping foil are estimated. Formulae for the emittance growth due to the multiple scattering in the stripper and to the ionization losses (in case of nonzero dispersion) are deduced. The additional momentum spread produced by the mean energy losses and the energy straggling is calculated. Two modes of ions storage are considered- with fixed and with moving orbit bumps. These relations are applied to the case of the NUCLOTRON's booster, now under design in JINR, Dubna.

1. INTRODUCTION

A booster synchrotron is being designed for the Dubna's superconducting heavy ion synchrotron NUCLOTRON, which was recently put in operation[1]. The booster will be a fast synchrotron with a circumference of 50m and a frequency 1Hz[2]. It will be able to accelerate ions up to 200 MeV/A and protons up to 650 MeV. The booster magnetic structure consists of six periods, each of them comprising two bending magnets and a quadruplet of quadrupole lenses. The betatron frequencies are $Q_x=Q_z=2.25$. The booster will give the NUCLOTRON new capabilities by increasing the beam intensity and the final energy. An electron cooling system is being also planned. The injection energy for Z/A=0.5 ions will be 5 MeV/A and 20MeV for protons.

The injection scheme will use the charge exchange method. This injection method is now a preferred one for the proton machines[3]; it has been recently successfully applied also for light ions storage[4]. In this work we try to analyse the possibility for the charge exchange injection to be applied for heavy ions storage. An analysis of the beam-stripper interaction processes and their reflection on the beam dynamics is made.

2. EQUILIBRIUM CHARGE DISTRIBUTION

The charge state distribution of the ions passing through the stripping foil reaches an equilibrium for thick enough foils[5]. This equilibrium distribution does not depend on the initial distribution and it is determined only by the relations between the electron loss and capture cross sections and the ion velocity. A lot of theoretical works on the cross-sections in ion-atom collisions have been carried out beginning with the pioneer works of Bohr and Lindhard. Unfortunately the experiments have shown that these results are valid only in a quite narrow parameters range. The problem is even more complicated in solid strippers. While in rare gases the time between the successive ion-atom collisions is long enough for the excited atoms to return to their basic state in the solid foils this time is short and the atom state keeps almost unchangeable. This means that all the cross-sections should be averaged over the excited states. For that reason a semi-empirical approach have been accepted. Usually the equilibrium charge state distribution is approximated by a Gaussian.Several empirical formulae have been proposed for the parameters of this Gaussian.For the average charge we have used the Shima's formula[6] which generalizes a wide range of experimental data; for the standard deviation we have used the formula of Nicolaev and Dmitriev.

Our calculations show that for 5 MeV/A Ar^{14+} and carbon foils with a thickness 100 $\mu g/cm^2$ the charge distribution has a maximum of 41.4% for q=17 while for q=16 the probability is 36.2%, for q=18 it is 12.5% and for q=15 only 8.3%. The 5 MeV/A light ions C^{5+} and Li^{2+} will be fully strippered (with 94% and 99% probabilities). We have taken these ions like basic ions in our estimations.

3. ION SCATTERING

An important role is played by the multiple scattering of the ions in the foil material. Changing the trajectory slopes it causes an emittance growth. To calculate this growth we will assume that the linear y and angular y deviations from the closed orbit are normally distributed. It follows from this that the betatron amplitude A has a Rayleigh distribution:

$$p(A) = \frac{A}{\sigma^2} e^{-\frac{A^2}{2\sigma^2}} \qquad (1)$$

[1]Work supported by NSF of Bulgaria,contract F-309.

Passing through the stripper the ions change by jump the slopes of their trajectories and keep unchangeable the linear deviation y. The new amplitude is:

$$A^2 = A_0^2 + 2\beta_0^2 y' \Delta y' + \beta_0^2 \Delta y'^2 \qquad (2)$$

β_0 being the β-function in the stripper and Δy the slope jump. Now we will take into account that at the end of the charge exchange injection process we will have on the circumference simultaneously particles passing N-times through the stripper ,particles passing (N-1) times through the stripper and so on up to the particles having crossed the stripper only once. Obviously the common distribution function is a normalized sum of the partial distribution functions:

$$p(A) = \frac{1}{N}\sum_{i=1}^{N} p_i(A) \qquad (3)$$

where N is the full number of the fulfilled turns. Averaging (2) and taking into account (3) one can obtain for the emittance growth:

$$\epsilon_N = \frac{\langle A^2 \rangle}{\beta_0} = \epsilon_0 + \frac{1}{2} N \beta_0 \langle \Delta y'^2 \rangle \qquad (4)$$

For the mean scattering angle we use the Moliere formula. The emittance growth for 5 MeV/A Ar^{14+}, C^{5+} and Li^{2+} ions are depicted on Fig.1.

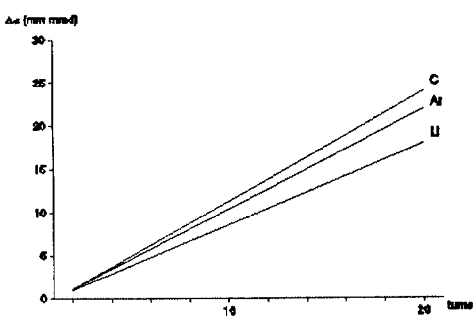

Figure 1.Emittance growth due to the multiple scattering.

4. MEAN ENERGY LOSSES

The mean energy losses in the stripping foil are given by the well-known Bethe-Bloch formula. If the dispersion in the foil is nonzero the mean energy losses will cause an emittance growth. A pure geometrical analysis gives:

$$\sqrt{\beta_0 \epsilon} = \sqrt{\beta_0 \epsilon_0} + k\sqrt{\Delta y^2 + \beta_0^2 \Delta y'^2} \qquad (5)$$

k being the turn number.

5. IONIZATION LOSSES STRAGGLING

The character of the ionization losses distribution depends on the parameter:

$$\kappa = \frac{\xi}{E_{max}} \qquad (6)$$

where:

$$\kappa = \frac{2\pi n e^4 Z_{pr}^2 Z_t x}{m_e V_{pr}^2} \qquad (7)$$

n-the number of target atoms per unit volume, x-the target thickness, Z_{pr}, v_{pr}- the ion charge and velocity, Z_t-the target atomic number.E_{max} is the maximum energy transfer.

When $\kappa < 0.05$ we have the case of Landau's distribution; when $0.05 < \kappa < 10$ - the Vavilov's one; when $\kappa > 10$ the distribution is a Gaussian.

In the case of NUCLOTRON's booster the calculations show that for 5 MeV/A Ar^{14+} ions the distribution is a Gaussian whereas for 5 MeV/A C^{5+} and Li^{2+} ions it is Vavilov's one.

The energy losses straggling affects the beam momentum spread. It turns out however that the final momentum spread depends stronger on the fact that at the end of the injection we have simultaneously on the orbit particles having crossed the foil N times, (N-1) times and so on up to one time. For that reason the final energy distribution is the envelope of all the N partial distributions, each of them shifted by the corresponding mean energy losses. The resulted energy dispersion is:

$$\langle \Delta E^2 \rangle_N = \langle \Delta E^2 \rangle_0 + \frac{N}{2} \langle \Delta^2 \rangle_t + \frac{N^2}{12} \langle \Delta \rangle_t^2 \qquad (8)$$

where Δ denotes the energy losses in the foil material.

The NUCLOTRON's booster additional momentum spread is shown on Figure 2.

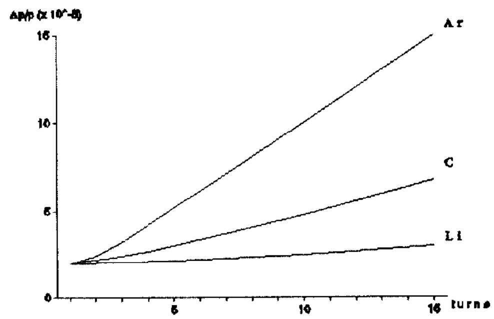

Figure 2. Additional momentum spread due to the energy losses.

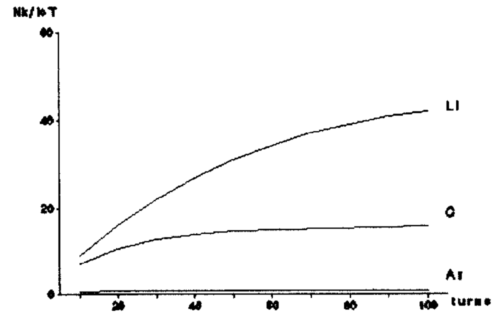

Figure 3. Ions storage- fixed orbit bump mode.

6. Ion Storage-Fixed Closed Orbit Bump Mode

In this mode the ions pass through the stripper until an equilibrium is attained or until other limited factors (scattering, energy losses) begin to restrict the stored particle number while the orbit bump keeps unchangeable. The number of stored particles is:

$$N_k = N_\infty (1 - b^k) \qquad (9)$$

where:

$$N_\infty = \left(\frac{a}{1-b}\right) I_0 T,\ a = \sigma_1 nt,\ b = \sigma_2 nt \qquad (10)$$

T-the period of the synchronous particle; I_0-the injector current; σ_1- the cross-section for the formation of ions with equilibrium charge from the injected ions; σ_2- the cross-section for the formation of ions with equilibrium charge from the circulating ions; nt- the foil thickness. For the targets of equilibrium thickness $\sigma_1 nt = \sigma_2 nt = \Phi_e$, Φ_e being the probability for equilibrium charge formation. The curves of the ion storage for the NUCLOTRON's booster are depicted on Figure 3.

7. Ion Storage- Moving Closed Orbit Bump Mode

In this mode the orbit bump is gradually reduced to zero during the injection. When the orbit is close to the center of the stripper the injected particles will cross it every turn. On the contrary particles injected when the orbit lies outside the stripper will undergo betatron oscillations and will avoid the stripper most of the turns. In other words we have a kind of combination between the multiturn and stripping injections.

Such a combination allows to increase the number of the injection turns many times. In order to estimate the number of stored particles in this mode we have developed a pure geometrical analysis in the normalized transverse phase plane. It shows that the number of stored particles can be increased more than five times.

8. References

[1] CERN Courier, vol.33, No6,pp.9-10, 1993.

[2] I.B.Issinsky, V.A.Mikhailov. "A 200 MeV/A Booster for the LHE Accelerator Complex", Preprint JINR Dubna,No P1-91-2, 1991.

[3] G.I.Dimov. Preprint of the INP Novosibirsk, No 304, 1969.

[4] K. Hedblom et al. "Calculation on Multiturn and Stripping Injection in CELSIUS", in Proceedings of 3-rd EPAC,Berlin, Germany, March 1992.

[5] I.S.Dmitriev et all. "On the Target Thickness to Attain Equilibrium Charge Distribution in a Beam of Fast Ions", Nucl. Instr. Meth., vol.B14, pp. 515-526, 1986.

[6] K.Shima et all. "Empirical Formula for the Average Equilibrium Charge-State of Heavy Ions Behind Various Foils", Nucl. Instr. Meth., vol.200, pp. 605-608, 1982.

[7] P.V.Vavilov. "Ionization losses of High Energy Heavy Particles", JETP, vol.32, pp.920-923, 1957.