Calculations on Multiturn and Stripping Injection in CELSIUS

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Abstract

In order to find the possible intensities of stored ions in CELSIUS we have made tracking computations. We first calculate the statistical acceptance of the injection process, then multiply the result with the expected phase space density in the incoming beam. The calculations have been made for stripping injection as well as multiturn injection. Stripping efficiency, energy loss, multiple scattering, and electron capture in the stripping foil are taken into account. To do this, we have developed useful formulae for stripping and capture.

We have also come across a new method of stripping injection, without any time varying elements in the ring at all. This is briefly discussed.

1. Introduction

The injection system of the CELSIUS ring [1] must be versatile enough to cope with a variety of conditions. Therefore, both multiturn and stripping injection schemes are used. Stripping injection allows the highest ratio between the stored beam current and the incoming beam current for light and moderately heavy ions, and is the preferred injection method, for protons (using H_2^+), deuterons (using D_2^+), α-particles (using He^+), and other ions up to Ar. Multiturn injection must be used to inject polarized protons and deuterons, which can only be produced as naked ions in our facility. Multiturn injection will also be used to inject protons of higher energies than 48 MeV, the maximum energy per nucleon with $Q/A = 1/2$ from our cyclotron. This will make it possible to share the cyclotron beam between the ring and other users at the same time (the other users generally require higher energies).

2. Injection Elements

The injection elements in the CELSIUS ring consist of electromagnetic and electrostatic septa, two bumper magnets, which displace the closed orbit during injection, and a thin stripper foil, mounted on a mechanism in the first bending magnet of the ring. The present foil is of carbon with thickness 30 $\mu g/cm^2$.

The bumper magnets are energized by the discharge of a capacitor through a thyratron. A resistor is connected in series with a free-wheeling diode across each magnet. Thus, the magnetic field in the magnets decreases exponentially after an initial rise to a maximum value. The time constant of the decrease is determined by the value of the resistor, and can be chosen in the interval from 4 μs to 4 ms. The injections take place during the exponential decrease of the magnetic field.

3. Multiturn Injection

During multiturn injection, the electrostatic septum is used to make the path of the injected beam different from the circulating beam path. During subsequent turns, the ions must always return at the inside of the septum foil in order not to hit the foil or be kicked out of the aperture by the electrical field. The time constant of decrease of the magnetic field in the bumper magnets must be chosen small enough.

4. Stripping Injection

During stripping injection the injected beam path is made different from that of the circulating beam by changing the charge to mass ratio of the ions in the stripping foil. The beam can traverse the foil a number of times, which is determined by the energy loss in the foil, the multiple scattering in the foil, and the probability for the ions to capture an electron in the foil. Therefore, during injection of light ions, the closed orbit can return to its normal position more slowly during stripping injection than during multiturn injection.

5. Tracking Computations

We have made tracking calculations in order to find the intensities to be expected with multiturn and stripping injection.

5.1 Method of tracking calculations.

To do the tracking calculations we first run the SPICE program [2] to obtain a table of bumper magnet bending angles as a function of time. We then find the acceptance of the injection process by tracking 4000 ions around the ring in the horizontal (x, x') and longitudinal (δ, ϕ) phase planes until they either are lost or safe inside the acceptance. The tracking is done by first order matrix transformations. At the bumper magnets, we change x' by an amount, which is taken from the SPICE output. At the rf. cavity, if the rf. voltage is chosen greater than zero, we change the momentum of the ion according to its phase and the rf. voltage. Each ion is attributed an initial "weight" corresponding to the calculated stripping efficiency in the foil (or 1 for multiturn injection). Aperture limitations are tested at each turn. If an ion is outside of these, its "weight" is set to zero. Each time an ion returns to the stripping foil, its momentum is decreased according to energy loss in the foil, its direction is changed to simulate multiple scattering in the foil, and its "weight" is multiplied by a factor corresponding to the probability for the ion not to capture any electron during the passage through the foil.

When the acceptance has been calculated the theoretical intensity multiplication factor is found by multiplying the "weight" of each ion with a factor proportional to the expected phase space density in the incoming beam.

5.2 Stripping

At the energies relevant for stripping injection in CELSIUS, and for not too heavy ions or too thin foils, we can assume that all except the K-shell electrons are removed with unit probability. For the stripping of the K-shell electrons against a light atom foil, a simple version of the cross section given by Bohr [3] can be used

$$\sigma_{strip} = 2 \cdot \frac{Z_F^{\,2} + Z_F}{Z^2} \cdot \frac{m_0 c^2 \alpha^2}{(T/A)} \cdot \pi a_0^{\,2}.$$

Here Z and Z_F are the atomic numbers of the projectile ions and the foil atoms respectively, (T/A) is the projectile kinetic energy per atomic mass unit, $\alpha = 1/137$ is the fine structure constant, $a_0 = 5.3 \times 10^{-11}$ m is the Bohr radius. The validity of the cross section is that (T/A) should be larger than $Z^2 m_0 c^2 \alpha^2$, while Z_F should not be much larger than Z. The probability of stripping both K-shell electrons is taken as the square of the one-electron stripping probability calculated according to the cross section given above.

5.3 Energy loss

The mean energy loss is calculated with the Bethe-Bloch equation.

In the tracking computations, we apply an energy loss ΔT to all ions that travel through the stripper foil according to the mean energy loss. We have also tested whether energy straggling plays a role in the stripping injection process by applying energy losses that are random distributed according to realistic energy loss distributions [4,5]. We found that in our case straggling does neither influence the intensity multiplication factor nor the resulting momentum spread in the stored beam. The momentum spread in the stored beam is dominated by the spread in the number of foil traversals for the ions rather than by the straggling in the foil.

5.4 Multiple scattering

We approximate the multiple scattering distribution with a normal distribution. Each time an ion travels through the foil, we change its direction by an amount taken from a normal distributed random number generator with standard deviation θ_{rms}, calculated according to Molière's theory with Fano's modification.

5.5 Electron capture

In the energy range relevant for injection in CELSIUS an important capture process is direct Coulomb capture mediated by electronic velocity matching

$$Z + (Z_F + e) \rightarrow (Z + e) + Z_F.$$

For completely stripped and not too heavy ions or target atoms, the dominant reaction is capture of K-shell target electrons into the K-shell of the projectile (since velocity matching with the slow electrons in higher shells is less probable). For projectile energies (T/A) higher than both $Z^2 m_0 c^2 \alpha^2$ and $Z_F^2 m_0 c^2 \alpha^2$, an estimate for the cross section for capture of one of the two K-shell electrons is

$$\sigma_{CC} = \frac{0.295 \cdot \frac{2^{19}}{5} \cdot (ZZ_F)^5 \left(\frac{2(T/A)}{m_0 c^2 \alpha^2}\right)^4 \pi a_0^2}{\left(\left(\frac{2(T/A)}{m_0 c^2 \alpha^2}\right) + (Z + Z_F)^2\right)^5 \left(\left(\frac{2(T/A)}{m_0 c^2 \alpha^2}\right) + (Z - Z_F)^2\right)^5}$$

The estimate is obtained from the Oppenheimer-Brinkman-Kramers (OBK) cross section through reduction to about 30 % as a correction for higher order terms [6] and with the velocity factor in the conventional form expressed in terms of the energy, which is of some importance when the relativistic velocity region is reached [7].

At sufficiently high energies electronic velocity matching becomes increasingly improbable and radiative electron capture can become important. In a first approximation the binding of the electron in the target atom can be neglected and for completely stripped ions the dominant reaction channel is capture to the K-shell

$$Z + e \rightarrow (Z + e) + h\nu.$$

The cross section for radiative electron capture from a target with Z_F electrons can be written

$$\sigma_{rec} = Z_F \frac{2^7}{3} \frac{\alpha^3}{g^5} \left(\frac{2\pi g^3 \exp\left(-\frac{4\arctan(g)}{g}\right)}{\left(1+g^2\right)^2 \left(1 - \exp\left(-\frac{2\pi}{g}\right)\right)} \right) \pi a_0^{\,2}$$

where

$$g = \sqrt{\frac{2(T/A)}{m_0 c^2 \alpha^2 Z^2}}.$$

This cross section is obtained from the one derived by Oppenheimer [8] by treating all target electrons as equivalent.

By inspecting the two cross sections discussed above, it is found that Coulomb electron capture dominates over radiative electron capture for energies (T/A) less than about $200 Z_F m_0 c^2 \alpha^2$. The stripping injection energies considered here fulfil this criterion, i.e. Coulomb capture is more important.

5.6 Results of tracking calculations

We have done the calculations for an incoming beam, which is normal distributed in momentum as well as horizontal position and angle. The rms. emittance is 2.5×10^{-6} m [9] and the rms. momentum spread is 1.65×10^{-3} [10]. We have found that the intensity multiplication factor can be estimated

$$\frac{I_{CELSIUS}}{I_{cyclotron}} = \eta_{strip} \tau_{foil} f_{rev}$$

where

$$\frac{1}{\tau_{foil}} = \frac{1}{\tau_{\Delta T}} + \frac{1}{\tau_\theta} \; ; \; \tau_{\Delta T} = \frac{3 \times 10^{-2} T}{f_{rev} \Delta T} \; ; \; \tau_\theta = \frac{7 \times 10^{-5} \,[\mathrm{m}]}{\beta^*_{foil} f_{rev} \theta^2_{rms}}$$

η_{strip} is the stripping probability, T is the kinetic energy of the ions, f_{rev} is the revolution frequency, and β^*_{foil} is the amplitude function at the foil.

The calculations show that for all ions except protons, the most important limitation to the lifetime is due to energy loss in the foil. For protons, the lifetime is limited by the multiple scattering in the foil. The limitation due to electron capture in the stripper foil is at least an order of magnitude less important. (In other rings, the situation can be quite different.)

It is an interesting observation, that the intensity multiplication factor does not depend on the stripper foil thickness, provided that the foil is thin enough, for the stripping probability to be proportional to the foil thickness.

The tracking calculations will be described in more detail in a forthcoming report [11].

6. ACCUMULATION

Both multiturn injection and stripping injection can be combined with accumulation with the electron cooling system [12-14]. Once the electron cooling has shrunk the transverse beam dimensions, the bumper magnets can be activated again in order to displace the closed orbit, without that the stored beam is lost, provided that the amplitude of the excitation is small enough that the stored beam is not displaced into the septum foil or stripper foil.

The intensities, which can be achieved with accumulation, are discussed in [12]. We take a recent run with stripping injection of oxygen as an example. For simplicity, the intensities are given in "particle μA." (1 particle μA = Q μA). The cyclotron was delivering 20 particle nA of O^{5+}. The tracking calculations show that with a single injection the stored beam intensity can be 25 times the cyclotron current, or 500 particle nA. With accumulation however, the bumper magnets must be excited with a smaller amplitude than what is optimal for single injections. We estimate that the closed orbit can then be moved half the way to the position of the stripper foil [12]. Then, the intensity multiplication factor for one injection is calculated to 15, corresponding to 300 particle nA. The delay between the injections was the minimum possible, 0.25 s; this must be longer than the cooling time, which is calculated to 0.15 s (the electron current was 300 mA). The revolution frequency in the ring was 725 kHz. Thus the expected rate of injected ions corresponds to 1.7 particle pA, or 8×10^{-5} of the available c.w. cyclotron beam current.

7. STRIPPING INJECTION WITH ELECTRON COOLING, WITHOUT USING THE BUMPER MAGNETS

Another way to do stripping injection has been found. This is without using any time-varying elements in the ring at all, but by making use of the electron cooling system. A small fraction of the beam is hitting the stripper foil at a position in phase space, which is so close to the acceptance, that the electron cooling system brings the ions into the acceptance fast enough that they never cross the foil again.

During a recent run with 300 MeV O^{5+} a stored beam current of 60 particle μA of O^{8+} was achieved in this way. The conditions were the same as mentioned in section 6 above. The rate of injected ions corresponded to about 1.2 particle pA, or 6×10^{-5} of the cyclotron current.

Since with this method of stripping injection most of the successful ions travel through the stripper foil only once, the optimal thickness of the foil depends on the ion species and energy, and is larger than with conventional stripping injection.

In practice, we have been much more successful to build up the intensity of heavy ions with this method, than with conventional accumulation at CELSIUS.

8. COMPARISON BETWEEN CALCULATED AND ACHIEVED STORED BEAM INTENSITIES

In the table below we summarize some achieved and calculated intensities of stored beams in CELSIUS.

ion	T/A $\left(\frac{\text{MeV}}{u}\right)$	method	computed multipl. factor	$I_{cycl.}$ (p. μA)	computed $I_{CELSIUS}$ (p. μA)	achieved $I_{CELSIUS}$ (p. μA)
H	48	strip	290	40	12000	18000
H	72	multit.	9	30	270	40
H	180	multit.	9	100	900	—
D	12	strip	110	10	1100	1000
He	12	strip	100	10	1000	1000
O	18	strip	25	0.02	0.5	0.1
O	12	str+acc	—	0.01	—	2
O	18	nobumps	—	0.02	—	60

9. REFERENCES

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