LIFETIME OF ION BEAM STORED IN HIRFL-CSR

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The relevant processes defining the survival of heavy ions in the cooler-storage ring— multiple Coulomb scattering, single Coulomb scattering, electron capture and electron stripping are described in this paper. The lifetime of stored ion beam at the injection energies as well as for a thin internal target experiment of HIRFL-CSR are estimated under the assumed vacuum conditions and target thickness.

1 Introduction

The investigation of beam lifetime in a heavy ion cooler-storage ring aims at determination of vacuum requirements, an internal target thickness and the allowable electron density in an electron cooler, because the loss of ions is determined by interaction with the residual gas molecules, target atoms and electrons in the e-cooler when the storage ring is operated at a stable working point.

At the injection energies the main factors defining the survival of ion beams are related to the following three processes.

(1). Single and multiple Coulomb scattering on residual gas molecules.

(2). Charge exchange(i.e. electron capture and electron stripping) with residual gas molecules.

(3). Radiative electron capture (REC) in the e-cooler.

The partial beam lifetime τ with respect to certain process is given by

$$\tau = \frac{1}{\sigma \cdot \rho_t \cdot \beta_i c}$$

where σ is the relevant cross section, ρ_t is the electron density in the e-cooler or the density of the residual gas atom with atomic number Z_t and $\beta_i c$ is the ion velocity.

Since less experimental data of cross sections for electron capture and electron loss by different heavy ions at energies between 5 MeV/u and 100MeV/u in different media (gaseous and solid) are available, our calculations of of e^{-1} beam lifetime in the proposed HIRFL-CSR[1] were based on approximation formulae.

Referring to the actually measured spectra[2][3] of residual gases, the average pressure of HIRFL-CSR in the following calculations is assumed to be 1.0×10^{-10} torr, with the residual gas composition of 85% H_2 and 15% (N_2, CO).

2 Lifetimes of Ion Beams at Injection Energies

2.1 Coulomb Scattering

(1) Single Scattering

Single scattering by an angle larger than an acceptance angle θ_{acc} results in an effective lifetime τ_{ss}:

$$\tau_{ss} = \frac{1}{\rho_t \cdot \beta_i c \cdot \int_{\theta_{acc}}^{\infty} \frac{d\sigma}{d\Omega} \cdot d\Omega} = \frac{\beta_i^3 \gamma_i^2 \cdot \theta_{acc}^2}{4\pi r_p^2 \cdot (\frac{Z_i}{A_i})^2 \cdot Z_t^2 \cdot c \cdot \rho_t}$$

where β_i,γ_i are relativistic factors of the ion with charge number Z_i and mass number A_i, r_p is the classical proton radius.

Taking into account the finite beam emittance, the ring acceptance angle θ_{acc} is approximately given by

$$\theta_{acc} = \sqrt{\frac{A_\perp}{\pi \langle \beta_\perp \rangle}}(1 - \frac{\epsilon_\perp}{A_\perp})$$

From the vertical acceptance of $A_v = 25\pi mm \cdot mrad$, the betatron value $\langle \beta_v \rangle \simeq 7m$ and the vertical emittance $\epsilon_v = 8\pi mm \cdot mrad$, one obtains $\theta_{acc} \simeq 1.3 mrad$.

The density of residual gas atoms can be calculated from the residual gas pressure P_{gas} and the atom numbers m_t per molecule as:

$$\rho_t[cm^{-3}] = 9.65 \times 10^{18} \times \frac{P_{gas}[torr]}{T(K)} \cdot m_t \simeq 3.5 \times 10^{16} \cdot P_{gas}[torr] \cdot m_t$$

The calculated values of τ_{ss} for typical heavy ions are given in table 1. Obviously, lifetimes due to single Coulomb scattering are long enough, and the influence to beam loss is quite small.

Table: 1 Beam lifetimes τ_{ss} caused by single scattering

Stored ion	Energy (MeV/u)	Lifetime (hrs)
$^{12}C^{6+}$	8.5	10.6
$^{14}N^{7+}$	8.5	10.6
$^{16}O^{8+}$	8.5	10.6
$^{20}Ne^{10+}$	8.5	10.6
$^{40}Ar^{18+}$	29.0	82.0
$^{84}Kr^{31+}$	12.0	32.6
$^{131}Xe^{44+}$	8.0	21.4
$^{181}Ta^{52+}$	5.0	14.5
$^{238}U^{61+}$	5.0	18.2

(2) Multiple Scattering

Multiple scattering with small angles results in an increase of angular spread of the beam , which can be calculated from eq.[2]:

$$\frac{d\langle\theta_i^2\rangle}{dt} \simeq 5.86\times10^{-4}\cdot P_{gas}\cdot m_t\cdot Z_t^2\cdot ln(204Z_t^{\frac{1}{3}})\cdot\left(\frac{Z_i}{A_i}\right)^2\cdot\frac{1}{\beta_i^3\gamma_i^2}$$

P_{gas} is measured in torr.

Emittance growth leads to the filling of the acceptance, when the emittance equals to the acceptance, further scatterings lead to beam loss. Therefore the lifetime caused by multiple scattering is given by:

$$\tau_{ms} = \frac{A_\perp - \epsilon_{\perp init}}{4\langle\beta_\perp\rangle\cdot\frac{d\langle\theta_i^2\rangle}{dt}}$$

$$= \frac{\beta_i^3\gamma_i^2\cdot(A_\perp - \epsilon_{\perp init})}{2.346\times10^{-3}\cdot P_{gas}\cdot m_t\cdot Z_t^2\cdot ln(204Z_t^{\frac{1}{3}})\cdot(\frac{Z_i}{A_i})^2\cdot\langle\beta_\perp\rangle}$$

where $A_\perp$ is the ring acceptance in the vertical plane.

The multiple scattering lifetimes for heavy ions at the injection energies are presented in table 2 . Compared with τ_{ss}, $\frac{\tau_{ms}}{\tau_{ss}} \simeq \frac{1}{20} - \frac{1}{30}$. When the emittance growth is compensated by electron cooling, the beam loss due to multiple Coulomb scattering can be neglected.

Table: 2 Beam lifetimes τ_{ms} caused by multiple scattering

Stored ion	Energy (MeV/u)	Lifetime
$^{12}C^{6+}$	8.5	1484.2 s
$^{14}N^{7+}$	8.5	1484.2 s
$^{16}O^{8+}$	8.5	1484.2 s
$^{20}Ne^{10+}$	8.5	1484.2 s
$^{40}Ar^{18+}$	29.0	3.2 hrs
$^{84}Kr^{31+}$	12.0	1.3 hrs
$^{131}Xe^{44+}$	8.0	3003.6 s
$^{181}Ta^{52+}$	5.0	2030.1 s
$^{238}U^{61+}$	5.0	2550.7 s

2.2 Charge Exchange with Residual Gas Molecules

Ions can be dropped out of the injected beam because of the change of charge state by capture or stripping of an electron.

(1) Electron Capture

With the help of Schlachter's empirical scaling rule[4] for electron capture, the cross section is determined by the relation:

$$\tilde{\sigma_c} = \frac{1.1\times10^{-8}}{\tilde{E}^{4.8}}[1-exp(-0.037\tilde{E}^{2.2})][1-exp(-2.44\times10^{-5}\tilde{E}^{2.6})]$$

where the reduced cross section $\tilde{\sigma_c} = \sigma_c\cdot Z_t^{1.8}/Z_i^{0.5}$, the reduced ion energy per nucleon $\tilde{E} = E_i/(Z_t^{1.25}\cdot Z_i^{0.7})$, σ is the cross section in cm^2 and E_i is the projectile energy in keV/A.

At the injection energies of CSRm, the square bracket terms can be neglected and one obtains:

$$\sigma_c = 1.1\times10^{-8}\cdot\frac{Z_i^{3.9}\cdot Z_t^{4.2}}{E_i^{4.8}}$$

For our assumed residual gas composition, the strong $Z_t^{4.2}$ dependence of the cross section leads to a dominance of the C, N, O fraction. From table 3 we can see that the heavier ions at lower energies survive for a time of second order because of the strong $Z_i^{3.9}/E_i^{4.8}$ dependence of capture cross section.

(2) Electron Stripping

The stripping cross sections of heavy ions with several electrons in light targets ($Z_i > Z_t$) can be calculated approximately by the modified Bohr's formula [2]:

$$\sigma_l = 4\pi a_0^2(Z_t^2 + Z_t)\left(\frac{\beta_i}{\alpha_s}\right)^{-2}\sum_{n=q_i}^{Z_i-1}\left(\frac{1}{B_n}\right)$$

where $B_n = Z_i^2/n^2$ (in units of 13.6 eV) is the binding energy of the electron in nth shell of the stored ion, $a_0 = 0.529 \times 10^{-10}m$ is the radius of Bohr's orbit, $\alpha_s = \frac{1}{137}$ is the fine structure constant.

For the partially stripped heavy ions (Kr–U), the stripping lifetimes are shown in table 4. Evidently, ion loss caused by electron stripping is negligible in contrast to the electron capture.

Table: 3 Beam lifetimes caused by electron capture

Stored ion	Energy (MeV/u)	Lifetime
$^{12}C^{6+}$	8.5	13.2 hrs
$^{14}N^{7+}$	8.5	7.3 hrs
$^{16}O^{8+}$	8.5	4.4 hrs
$^{20}Ne^{10+}$	8.5	1.8 hrs
$^{40}Ar^{18+}$	29.0	37.9 hrs
$^{84}Kr^{31+}$	12.0	384.3 s
$^{131}Xe^{44+}$	8.0	36.0 s
$^{181}Ta^{52+}$	5.0	9.1 s
$^{238}U^{61+}$	5.0	6.5 s

Table: 4 Beam lifetimes caused by electron loss

Stored ion	Energy (MeV/u)	Lifetime (sec)
$^{84}Kr^{31+}$	12.0	1357.9
$^{131}Xe^{44+}$	8.0	2502.5
$^{181}Ta^{52+}$	5.0	604.0
$^{238}U^{61+}$	5.0	959.0

2.3 Radiative Electron Capture in the Electron Cooler

The rate for the radiative electron capture in lab frame is connected with the recombination coefficient α_r by[5]

$$R_r = -\frac{1}{N_i}\frac{dN_i}{dt} = \frac{\alpha_r \cdot n_e \cdot \eta}{\gamma_i^2}$$

in which n_e is the electron density in the e-cooler, η is the ratio of the cooling section length and the ring circumference(for CSRm $\eta = 0.02$). α_r is defined as the expectation value of REC cross section folded with the relative velocity between electrons and ions:

$$\alpha_r = \langle \sigma_r \cdot v \rangle$$

For a flattened electron velocity distribution, α_r can be expressed in a closed form[6]:

$$\alpha_r = 3.02\times10^{-13} Z_i^2 \cdot (kT_e)^{-\frac{1}{2}} \cdot \left\{ \ln[11.32 Z_i \cdot (kT_e)^{-\frac{1}{2}}] + \left(\frac{kT_e}{Z_i^2}\right)^{\frac{1}{3}} \right\}$$

where kT_e is the transverse electron beam temperature in eV, α_r is in $cm^3 \cdot s^{-1}$,

Therefore the lifetime due to REC is defined as:

$$\tau_r = \frac{\gamma_i^2}{\alpha_r \cdot n_e \cdot \eta}$$

From the above two equations, τ_r is expected to scale with n_e^{-1},Z_i^{-2} and $(kT_e)^{\frac{1}{2}}$.

For the calculation of related REC lifetime, assuming all the heavy ions at the injection energies are stripped completely, and the electron current densities are high enough in order to obtain strong cooling rates during RF stacking. The REC lifetimes at relevant electron currents are given in table 5. Fig. 1 demonstrates the lifetime versus electron current densities.

Table: 5 Beam lifetimes caused by REC

Stored ion	Energy (MeV/u)	Electron current (Ampere)	REC lifetime
$^{12}C^{6+}$	8.5	1.0	1.5 hrs
$^{14}N^{7+}$	8.5	1.0	1.0 hrs
$^{16}O^{8+}$	8.5	1.0	2796.5 s
$^{20}Ne^{10+}$	8.5	1.0	1718.7 s
$^{40}Ar^{18+}$	29.0	1.2	759.3 s
$^{84}Kr^{31+}$	12.0	0.4	440.0 s
$^{131}Xe^{44+}$	8.0	0.2	340.2 s
$^{181}Ta^{52+}$	5.0	0.1	374.4 s
$^{238}U^{61+}$	5.0	0.1	266.4 s

Comparing the above five reactions, we finally obtained the shortest partial lifetimes which are compiled in table 6. In conclusion, the REC process in the electron cooler restricts the lifetimes of light heavy ions (C–Ar), the electron capture mechanism dominates the lifetimes of heavier ions (Kr–U), and the beam loss caused by Coulomb scattering is negligible. The lifetimes of stored ion beams at the injection energies are longer than the time what we need for stacking injection ($\sim$ 5 s) and electron cooling ($\sim$ 1s). This allows to obtain high intensity accumulated ion beams.

Table: 6 Lifetimes of ion beams

Stored ion	Energy (MeV/u)	Lifetime
$^{12}C^{6+}$	8.5	1.5 hrs
$^{14}N^{7+}$	8.5	1.0 hrs
$^{16}O^{8+}$	8.5	2796.5 s
$^{20}Ne^{10+}$	8.5	1718.7 s
$^{40}Ar^{18+}$	29.0	759.3 s
$^{84}Kr^{31+}$	12.0	206.0 s
$^{131}Xe^{44+}$	8.0	36.0 s
$^{181}Ta^{52+}$	5.0	9.1 s
$^{238}U^{61+}$	5.0	6.5 s

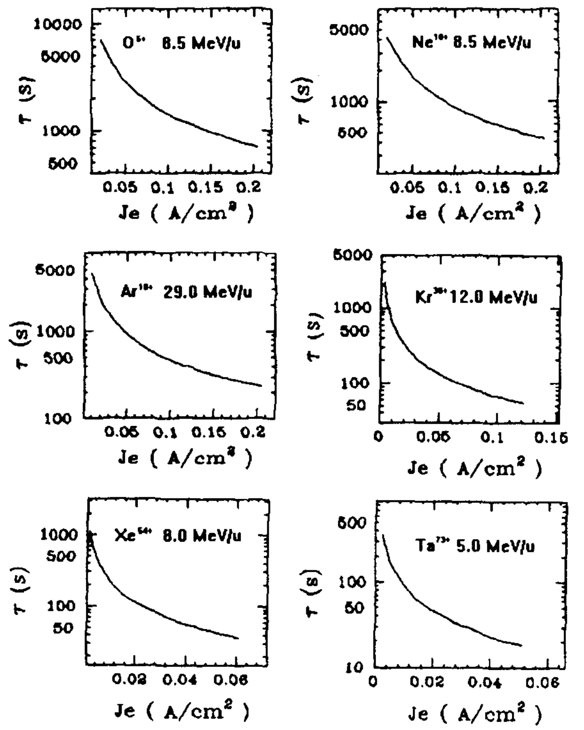

Figure:1 REC Beam Lifetime vs. e current density, $kT_e = 0.2eV$, $\eta = 0.02$

3 Lifetimes of ion beams for internal target experiments

Besides the three processes mentioned above, the following two factors have to be taken into account when determining lifetimes of ion beams for thin internal target experiments.

(1). Charge exchange with target atoms,

(2). Coulomb scattering on target atoms.

Electron capture on target atoms dominates the circulating beam lifetimes, and the Coulomb scattering can be compensated by the electron cooling. As an example, table 7 demonstrates the lifetimes, which were roughly estimated by using Schlachter's formula, for the heavier internal target experiments: $^{12}C^{6+} +^{208}_{82} Pb$, $^{84}Kr^{36+} +^{208}_{82} Pb$, $^{238}U^{92+} +^{208}_{82} Pb$, assuming the projectile energies of 10, 100, 250 MeV/u respectively and target thickness of $10^{15} atoms/cm^2$.

Table: 7 Lifetimes of ion beams for internal target experiments

Projectile	Projectile energy (MeV/u)	Target thickness ($atoms/cm^2$)	lifetime
$^{12}C^{6+}$			15.05 ms
$^{84}Kr^{36+}$	10		965.84μs
$^{238}U^{92+}$			502.00μs
$^{12}C^{6+}$			4.54 s
$^{84}Kr^{36+}$	100	1.0×10^{15}	23.05 ms
$^{238}U^{92+}$			3.12 ms
$^{12}C^{6+}$			256.62 s
$^{84}Kr^{36+}$	250		281.52 ms
$^{238}U^{92+}$			19.66 ms

For the low energy heavy ion reaction, electron capture leads to serious loss of ion beams. Therefore CSRe internal target thickness is defined as $10^{15} atoms/cm^2$. However, it should be emphasized that if using a target lighter than Pb, the stored beam lifetimes will be longer, and it will result in higher experimental luminosities.

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