Loss mechanisms and lifetimes of heavy ion beams in HIRFL-CSRe

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Abstract. The loss mechanisms and lifetimes of ion beams in a cooler storage ring in collisions with residual gas, internal gaseous target, and electrons in an electron-cooler were studied. Partial beam lifetimes, which were due to various loss mechanisms, and total beam lifetimes of 50-500 MeV/u $^{12}$C$^{6+}$, $^{36}$Ar$^{18+}$, $^{132}$Xe$^{54+}$ and $^{238}$U$^{92+}$ ion beams stored in HIRFL-CSRe were also calculated. The calculations indicate that the beam lifetimes are restricted considerably by charge exchange between the beam ions and the internal gaseous target, as well as radiative recombination with the electrons. For heavy ion beams such as $^{132}$Xe$^{54+}$ and $^{238}$U$^{92+}$, the radiative recombination with electrons in the electron-cooler is the main loss mechanism.

1. Introduction
The loss mechanisms and lifetimes of ion beams circulating in a cooler storage ring are routinely considered in various cooler storage rings experimentally and/or theoretically [1-7]. The lifetime of an ion beam mainly depends on the interaction between the ions and the residual gas, internal gaseous target, and electrons in the electron-cooler. The main processes include single Coulomb scattering, multiple Coulomb scattering and charge exchange between the beam ions and the residual gas or internal gaseous target, as well as radiative recombination, which occurs during the interaction of the beam ions with the cooling electrons.

In this work the loss mechanisms and lifetimes of heavy ion beams circulating in HIRFL-CSRe—the experimental ring of the newly finished Cooler-Storage-Ring system HIRFL-CSR in Lanzhou [8] were studied. Partial beam lifetimes, which were due to various loss mechanisms, and total beam lifetimes of 50-500 MeV/u $^{12}$C$^{6+}$, $^{36}$Ar$^{18+}$, $^{132}$Xe$^{54+}$ and $^{238}$U$^{92+}$ ion beams stored in HIRFL-CSRe in collisions with the residual gas (3.0×10$^{-11}$ m^3, 85% H$_2$, 15% N$_2$), internal gaseous target (N$_2$: 5.0×10$^{12}$ atoms/cm$^3$) and electrons in the electron-cooler (5×10$^7$ electrons/cm$^3$) were calculated.

2. Beam lifetime due to interaction with residual gas
For each beam loss mechanism due to the interaction with residual gas, the corresponding lifetime can be expressed as

$$\tau_j = (\sigma_j \rho \beta c)^{-1},$$

where $\sigma_j$ is the corresponding interaction cross section such as single Coulomb scattering [9], multiple Coulomb scattering [9-11], electron capture [12-25] or electron loss [1, 13, 20, 22, 26-32]. For simple molecules such as H$_2$, CO, CO$_2$ and N$_2$, $\sigma_j$ could be obtained by adding together the
individual cross section of each atom in the molecule if the velocity of the ion beam is high. \( \rho_r \) is the number density of the residual gas [33], and \( \beta_i \) is the ion beam velocity in units of \( c \times 10^8 \text{ m/s} \).

If the residual gas consists of two components, \( a \) and \( b \), the corresponding beam lifetime is [11]

\[
(\tau_{ij}) = \left((\sigma_{ji} \rho_{ra} \beta_i c) + (\sigma_{ji} \rho_{rb} \beta_i c)^{-1}\right)^{-1},
\]

where \( \rho_{ra} \) and \( \rho_{rb} \) are the number densities of \( a \) and \( b \), respectively.

The total beam lifetime resulting from the interaction with the residual gas can be described as

\[
(\tau_r) = \left(\sum_j (\tau_{ij})^{-1}\right)^{-1}.
\]

3. Beam lifetime due to interaction with internal gaseous target

The interaction processes between the beam ions and the internal gaseous target are similar to those with the residual gas, namely single Coulomb scattering, multiple Coulomb scattering, electron capture and electron loss. However, the beam lifetime related to each loss mechanism should be described as

\[
(\tau_{ij}) = (\sigma_{ji} \rho_i f_0)^{-1},
\]

where \( \rho_i \) is the area number density of the target and \( f_0 \) is the revolution frequency of the ion beam. Additionally, the beam lifetime due to energy loss can be found in Boine-Frankenheim’s work [6].

4. Beam lifetime due to interaction with electrons in the electron-cooler

To lower (or eliminate) the transverse and longitudinal emittance increasing in the cooler storage ring caused by Coulomb scattering and intra-beam scattering, the electron cooling is used. However, radiative recombination during the interaction of the beam ions with the cooling electrons can cause beam loss. The corresponding lifetime can be expressed as [11]

\[
(\tau_{rec}) = \gamma_i^{-1} \alpha^{-1} n_e^{-1} \eta_{rec}^{-1}.
\]

Here, \( \gamma_i = (1 - \beta_i^2)^{-1} \), \( \alpha \) is the recombination coefficient in \( \text{cm}^3/\text{s} \) [34], \( n_e \) is the number density of the electrons in \( \text{cm}^3 \), and \( \eta_{rec} \) is the ratio of the cooling length to the ring circumference.

5. Total beam lifetime

Under the influence of the residual gas, internal gaseous target and electrons in the electron-cooler, the total beam lifetime can be expressed by

\[
(\tau_{total}) = \left(\tau_r^{-1} + \tau_i^{-1} + \tau_{rec}^{-1}\right)^{-1},
\]

where \( \tau_r \), \( \tau_i \) and \( \tau_{rec} \) are the partial beam lifetimes due to interaction with the residual gas, internal gaseous target and electrons in the electron-cooler, respectively.

We used the method in the reference [9] to predict the cross sections of single Coulomb scattering. Partial beam lifetimes due to multiple Coulomb scattering and energy loss were investigated according to the way published by [7,10] and [6], respectively. For fast ion beams such as \( \text{Xe}^{54+} \) and \( \text{U}^{92+} \) with the light target, the cross sections of the dominate electron capture channel, radiative electron capture, were obtained by interpolating in published data table II of Mclaughlin’s work [24], and then timing the quasifree electrons in the light target. For \( \text{C}^{6+} \) and \( \text{Ar}^{18+} \), we used the equation (5) in Franzke’s work [7] to calculate the electron capture cross sections. Then, the beam lifetime of \( \text{238U}^{92+} \) stored in ESR [4] were calculated and compared with their experimental data in table 1.

Furthermore, according to the main parameters of the HIRFL-CSRe, the partial lifetimes as well as the total lifetimes of 50-500 MeV/u \( \text{12C}^{6+} \), \( \text{36Ar}^{18+} \), \( \text{132Xe}^{54+} \) and \( \text{238U}^{92+} \) in collisions with the residual gas (3.0\times10^{11} \text{mbar}, 85\% \text{H}_2, 15\% \text{N}_2), internal gaseous target (\text{N}_2: 5.0\times10^{12} \text{atoms/cm}^2) \) and electrons in the electron-cooler (5\times10^7 \text{electrons/cm}^2) were calculated and listed in table 2.
Table 1. Calculated and experimental beam lifetime of U\textsuperscript{92+} in ESR.

| Ion   | Energy (MeV/u) | Target          | Present work (not cooled) | Experimental data [4] (not cooled) |
|-------|----------------|-----------------|---------------------------|-----------------------------------|
| U\textsuperscript{92+} | 49             | N\textsubscript{2}(5.0\times10\textsuperscript{11} mol./cm\textsuperscript{2}) | 146 | 80 |
|       | 68             | N\textsubscript{2}(5.0\times10\textsuperscript{11} mol./cm\textsuperscript{2}) | 197 | 130 |
|       | 220            | N\textsubscript{2}(5.0\times10\textsuperscript{11} mol./cm\textsuperscript{2}) | 668 | 750 |
|       | 358            | N\textsubscript{2}(5.0\times10\textsuperscript{11} mol./cm\textsuperscript{2}) | 1230 | 1300 |

Comparing the calculations with the experimental data in table 1, we overestimate the lifetimes of \textsuperscript{238}U\textsuperscript{92+} at low energy, but underestimate them at high energy. This is because we do not take the non-radiative electron capture into account, which becomes important in the collision between the highly charged heavy ions and the light target at low energy. The ratio of the calculated lifetime to the experimental data ranges from 0.9 to 1.9.

For 50-500 MeV/u \textsuperscript{12}C\textsuperscript{6+}, \textsuperscript{36}Ar\textsuperscript{18+}, \textsuperscript{132}Xe\textsuperscript{54+} and \textsuperscript{238}U\textsuperscript{92+} circulating in HIRFL-CSRe, the calculations indicate that:

1) The loss mechanisms resulting from the residual gas, with an average pressure of 3.0\times10\textsuperscript{-11} mbar, can be neglected.

Table 2. Partial and total lifetimes of 50-500 MeV/u \textsuperscript{12}C\textsuperscript{6+}, \textsuperscript{36}Ar\textsuperscript{18+}, \textsuperscript{132}Xe\textsuperscript{54+} and \textsuperscript{238}U\textsuperscript{92+} stored in HIRFL-CSRe.

| Ion   | Energy (MeV/u) | \(\tau_\text{r}(s)\) | \(\tau_\text{t}(s)\) | \(\tau_\text{rr}(s)\) | \(\tau_\text{total}(s)\) |
|-------|----------------|----------------|----------------|----------------|----------------|
| \textsuperscript{12}C\textsuperscript{6+} | 50             | 1.91\times10\textsuperscript{5} | 1.79\times10\textsuperscript{4} | 3.77\times10\textsuperscript{3} | 1.71\times10\textsuperscript{2} |
|       | 100            | 8.73\times10\textsuperscript{5} | 7.68\times10\textsuperscript{4} | 4.17\times10\textsuperscript{3} | 6.48\times10\textsuperscript{2} |
|       | 200            | 3.66\times10\textsuperscript{6} | 3.03\times10\textsuperscript{4} | 5.02\times10\textsuperscript{3} | 1.89\times10\textsuperscript{3} |
|       | 300            | 7.55\times10\textsuperscript{6} | 6.28\times10\textsuperscript{4} | 5.94\times10\textsuperscript{3} | 3.05\times10\textsuperscript{3} |
|       | 400            | 1.16\times10\textsuperscript{7} | 1.00\times10\textsuperscript{5} | 6.95\times10\textsuperscript{3} | 4.10\times10\textsuperscript{3} |
|       | 500            | 1.52\times10\textsuperscript{7} | 1.39\times10\textsuperscript{4} | 8.03\times10\textsuperscript{3} | 5.09\times10\textsuperscript{3} |
| \textsuperscript{36}Ar\textsuperscript{18+} | 50             | 5.62\times10\textsuperscript{4} | 5.52\times10\textsuperscript{3} | 3.54\times10\textsuperscript{2} | 2.15\times10\textsuperscript{2} |
|       | 100            | 1.39\times10\textsuperscript{5} | 1.41\times10\textsuperscript{4} | 3.90\times10\textsuperscript{3} | 1.04\times10\textsuperscript{4} |
|       | 200            | 8.00\times10\textsuperscript{5} | 7.98\times10\textsuperscript{4} | 4.70\times10\textsuperscript{3} | 2.96\times10\textsuperscript{4} |
|       | 300            | 2.24\times10\textsuperscript{6} | 2.22\times10\textsuperscript{4} | 5.57\times10\textsuperscript{3} | 4.45\times10\textsuperscript{4} |
|       | 400            | 4.42\times10\textsuperscript{6} | 4.48\times10\textsuperscript{4} | 6.51\times10\textsuperscript{3} | 5.68\times10\textsuperscript{4} |
|       | 500            | 7.02\times10\textsuperscript{6} | 7.42\times10\textsuperscript{4} | 7.52\times10\textsuperscript{3} | 6.83\times10\textsuperscript{4} |
| \textsuperscript{132}Xe\textsuperscript{54+} | 50             | 1.39\times10\textsuperscript{5} | 1.40\times10\textsuperscript{4} | 33.8 | 27.2 |
|       | 100            | 2.99\times10\textsuperscript{5} | 3.05\times10\textsuperscript{4} | 37.3 | 33.2 |
|       | 200            | 7.12\times10\textsuperscript{5} | 7.43\times10\textsuperscript{4} | 44.9 | 42.3 |
|       | 300            | 1.24\times10\textsuperscript{6} | 1.33\times10\textsuperscript{4} | 53.2 | 51.1 |
|       | 400            | 1.87\times10\textsuperscript{6} | 2.07\times10\textsuperscript{4} | 62.2 | 60.4 |
|       | 500            | 2.57\times10\textsuperscript{6} | 2.95\times10\textsuperscript{4} | 71.9 | 70.2 |
| \textsuperscript{238}U\textsuperscript{92+} | 50             | 3.38\times10\textsuperscript{5} | 35.3 | 10.9 | 8.3 |
|       | 100            | 6.45\times10\textsuperscript{5} | 67.7 | 12.0 | 10.2 |
|       | 200            | 1.34\times10\textsuperscript{6} | 1.42\times10\textsuperscript{4} | 14.5 | 13.1 |
|       | 300            | 2.18\times10\textsuperscript{6} | 2.32\times10\textsuperscript{4} | 17.1 | 16.0 |
|       | 400            | 3.17\times10\textsuperscript{6} | 3.40\times10\textsuperscript{4} | 20.0 | 18.9 |
|       | 500            | 4.30\times10\textsuperscript{6} | 4.65\times10\textsuperscript{4} | 23.2 | 22.1 |

Comparing the calculations with the experimental data in table 1, we overestimate the lifetimes of \textsuperscript{238}U\textsuperscript{92+} at low energy, but underestimate them at high energy. This is because we do not take the non-radiative electron capture into account, which becomes important in the collision between the highly charged heavy ions and the light target at low energy. The ratio of the calculated lifetime to the experimental data ranges from 0.9 to 1.9.
2) With the increase of energy, the beam lifetimes become longer, and the light ion beams can be stored longer than the heavy ones with the same energy.

3) Lifetimes of $^{12}$C$^{6+}$ and $^{36}$Ar$^{18+}$ are several tens of minutes, mainly due to charge exchange between the beam ions and the internal gaseous target, as well as radiative recombination with electrons in the electron-cooler.

4) $^{132}$Xe$^{54+}$ and $^{238}$U$^{92+}$ ion beams can be stored only for several tens of seconds in HIRFL-CSRe. The main loss mechanism is radiative recombination with the cooling electrons.

The calculations and conclusions presented here will be very helpful for the experiments at HIRFL-CSRe.

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