EFFECT OF GOLD NUCLEI RECOMBINATION IN ELECTRON COOLING SYSTEM ON BEAM LIFETIME IN THE NICA COLLIDER

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Abstract

On the basis of experimental data the production of the ions Au^{78+} and Au^{77+} as a result of step-by-step radiative recombination of bare nuclei on free electrons in the NICA Collider electron cooling system is presented. The influence of Au^{78+} ions on the luminosity lifetime is discussed. The optimum working cycle of the NICA Collider is described.

LUMINOSITY LIFETIME

The NICA Collider working cycle will consist of the following modes: collision mode during time T and reloading mode during time ΔT. The average luminosity $\langle L(T)\rangle$ can be estimated using the following formula:

$$\langle L(T)\rangle = \frac{\int_0^T L(t)\,dt}{T+\Delta T}. \quad (1)$$

For the round beams the peak luminosity $L_{\max}$ can be calculated in accordance with the formula:

$$L_{\max} = \frac{N^2}{4\pi\varepsilon_\perp \beta^*} F_{\text{coll}} f_{\text{HG}}\left(\frac{\sigma_s}{\beta^*}\right). \quad (2)$$

Where N is the bunch intensity; $\varepsilon_\perp$ is the transverse unnormalized rms emittance; β^* is the beta function in the interaction point; σ_s is the rms value of the longitudinal beam size; F_{coll} is the collision repetition frequency and factor f_{HG} is define the hour glass effect. When the emittance and bunch length are stabilized by electron cooling (we assume that the cooling power is adjusted for exact compensation of the beam heating due to intrabeam scattering process) the luminosity lifetime is determined by the bunch intensity variation only:

$$\frac{1}{L}\frac{dL}{dt} = 2\frac{1}{N}\frac{dN}{dt}.$$

During the collision mode the ion losses lead to decrease of the total beam intensity by the value ΔN (in each ring of the NICA Collider). Thereafter one needs to provide debunching of the beam, injection of a few portions of the ions from the Nuclotron and beam bunching to prolong the collisions. The time ΔT required for these procedures can be estimated approximately to $\Delta T = 250$ s [3]. In this estimation the beam preparation time that describes the full period of time required for the beam debunching and adiabatic capturing in the NICA Collider (in the estimations below we used rather optimistic value of 10 s).

Maximizing the average luminosity (1) we can obtain optimum duration for the collision mode of the NICA Collider operation.

More powerful process leading to the ion losses during the collisions is the radiative recombination (RR) of gold ions on free electrons in the NICA Collider electron cooling system i.e.:

$$\frac{1}{L}\frac{dL}{dt} \propto -\frac{2}{\tau^{\text{RR}}}. \quad (3)$$

Here τ^{RR} is the characteristic time of the bunch intensity variation due to RR process.

In this case the average luminosity (1) can be written as follows:

$$\langle L(T)\rangle = \frac{\tau^{\text{RR}}}{T+\Delta T(T)}\cdot\frac{1-e^{-2T/\tau^{\text{RR}}}}{2}\cdot L_{\max}. \quad (4)$$

Resume all that was said above the information about beam intensity kinetics is needed.

BEAM INTENSITY KINETICS DUE TO RR PROCESS

The analysis of Au^{79+} bare nuclei and Au^{78+}, Au^{77+} ions beam formed in the NICA Collider electron cooling system in energy range of 1÷4.5 GeV/u has shown (Fig. 1) that most of the Au^{77+} ions will be lost at the vacuum chamber aperture $r_x = 60$ mm during approximately 1.8 µs (one revolution period). The amount of surviving Au^{77+} ions increases with beam energy but does not exceed 5% at 4.5 GeV/u. In this case for our goal it is sufficient to consider RR process of Au^{79+} bare nuclei into Au^{78+} ions. The ions of lower charge states can be neglected because they lost on vacuum chamber aperture at the first turn in the NICA Collider ring after their generation.

Therefore the set of kinetic equations describing formation of Au^{78+} ions owing to RR process of Au^{79+} bare nuclei on free electrons in the NICA Collider cooling system can be written as follows:

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$$\begin{cases} \dfrac{dN_{79}}{dt} = -\dfrac{N_{79}}{\tau_{79}}, \\ \dfrac{dN_{78}}{dt} = -\dfrac{N_{78}}{\tau_{78}} + \dfrac{N_{79}}{\tau_{79}}(1-\delta_{78}), \\ N_{79}(0) = N_{79,0}, \quad N_{78}(0) = 0. \end{cases} \quad (5)$$

The closed orbits of Au^{79+} bare nuclei and ion beams Au^{77+}, Au^{78+} are shown on Fig. 1.

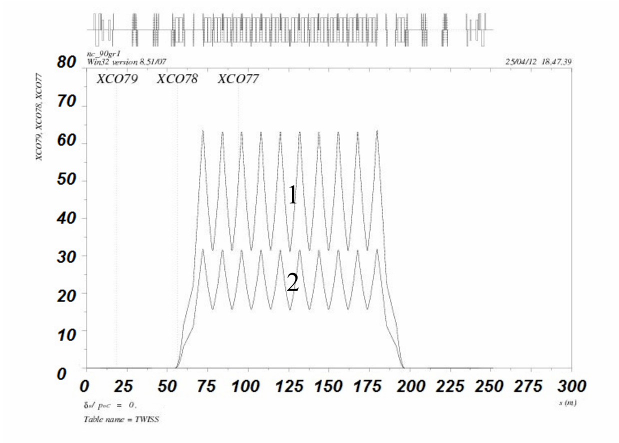

Figure 1: Closed orbits of ion beams 1 — Au^{77+} and 2 — Au^{78+}; the closed orbit of Au^{79+} bare nuclei coincides here with abscissa axis.

The analytical solution of equations set (5) can be written as follows:

$$N_{79}(t) = N_{79,0} e^{-t/\tau_{79}},$$
$$N_{78}(t) = N_{79,0}(1-\delta_{78}) \frac{\tau_{78}}{\tau_{78}-\tau_{79}} \left(e^{-t/\tau_{79}} - e^{-t/\tau_{78}}\right). \quad (6)$$

Here N_{78} and N_{79} the beam intensities of Au^{78+} ions and Au^{79+} nuclei. Symbols τ_{78} and τ_{79} designate the RR times of Au^{78+} ions and Au^{79+} bare nuclei; $\delta_{78} \le 1$ designate loss factor of Au^{78+} ions on vacuum chamber wall due to the beam dynamics during a time less than the betatron oscillations.

With using (6) the effective RR time τ^{RR} in (4) can be found from following:

$$\tau^{RR} = \frac{\tau_{79}}{\delta_{78} + x\tau_{79}/\tau_{78}} \cdot (1+x), \quad x = \frac{N_{78}}{N_{79}}. \quad (7)$$

For further estimations in (7) we used the values for RR time τ_{79} and ratio τ_{79}/τ_{78} (~ 10) based on experimental data [2].

RESULTS AND CONCLUSION

The dependencies of lost factor δ_{78} as function of beam energy E was taken from the results of article [1]. These dependencies were calculated for two particle distributions in the bunch, i.e. Gauss and Kapchinsky-Vladimirsky (homogeneous charge density) ones. Below this results are shown in Fig. 2. The ion beam emittance $\varepsilon_{\perp} = 1.1$ π·mm·mrad was taken into account.

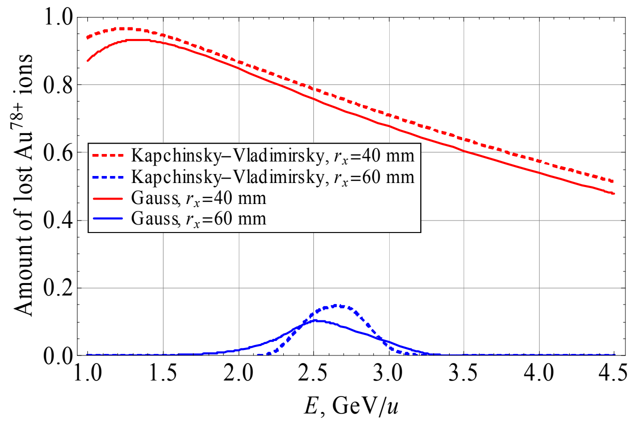

Figure 2: Loss factor δ_{78} of ion beam Au^{78+} as function of beam energy E.

Variation of the vacuum chamber aperture from $r_x = 40$ mm up to $r_x = 60$ mm leads to insignificant variation of the loses factor δ_{78} (about 10÷15%) so the influence of ion losses on beam intensity kinetics is small (Figs. 3-5 below). On Figs. 3-5 N/N_0 is ratio of beam intensity to initial value; t/τ_{79} is the time in units of RR time of Au^{79+} bare nuclei; $T_{\perp,e}$ and I_e transverse temperature of electron beam and electron beam current correspondingly; τ_{cool} is the cooling time [1].

As a conclusion we can say the following:

- RR process of Au^{79+} bare nuclei on free electrons in the NICA Collider electron cooling system leads to formation of Au^{77+} and Au^{78+} ion beams;
- For vacuum chamber aperture $r_x = 60$ mm the number of surviving ions Au^{77+} does not exceed 5% at 4.5 GeV/u;
- In contrary Au^{78+} ions have significantly long lifetime; for improving the vacuum conditions the special collimators (catchers) to clean the vacuum chamber from the charge-exchanged beam of Au^{78+} ions can be installed. For vacuum chamber aperture $r_x = 40$ mm the analysis of (4) gives us the average luminosity values shown in Table 1 at $T = \tau^{RR}$. The reloading time is the same for all these energies and equal approximately to $\Delta T \approx 250$ s [3].

Table 1: The NICA Collider electron cooling parameters for optimal working regime at peak luminosity $L_{max} = 10^{27}$ cm^{-2}·s^{-1}.

E, GeV/u	**I_e, A**	**$T_{\perp,e}$, eV**	**$\tau^{RR}/\tau^{cool}/\tau^{IBS}$, s**	**L/L_{max}**
1	0.3	2	1000/140/186	0.4
3	1.3	2	1070/680/702	0.4
4.5	1.5	2	1800/2400/2540	0.4

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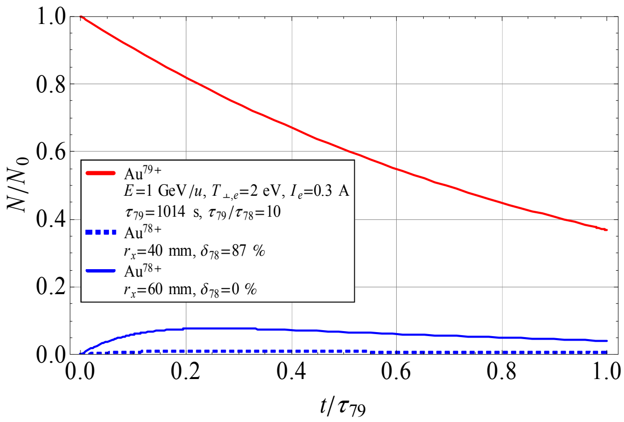

Figure 3: Solution (6) for beam energy E = 1 GeV/u.

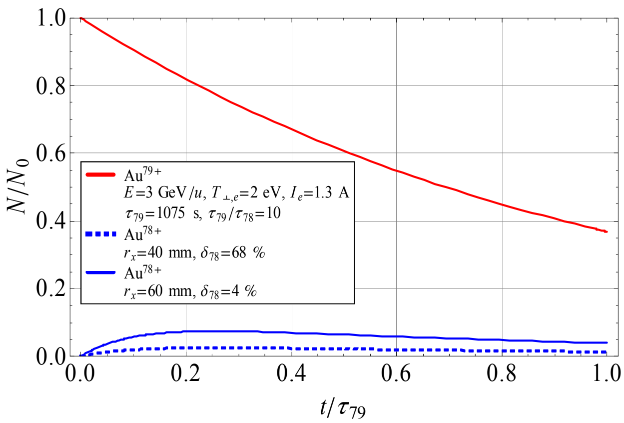

Figure 4: Solution (6) for beam energy E = 3 GeV/u.

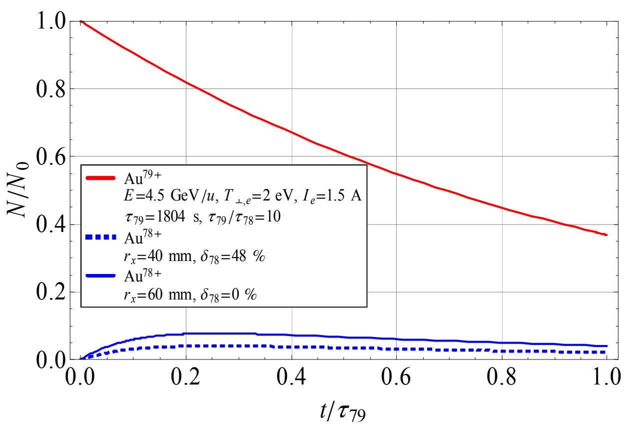

Figure 5: Solution (6) for beam energy E = 4.5 GeV/u.

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