GOLD IONS BEAM LOSSES AT THE NUCLOTRON BOOSTER

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Abstract

The calculation results of the gold ions beam losses along the Nuclotron Booster perimeter are given. The presented results take the ion stimulated desorption from the cold surface of the vacuum chamber and collimation of charge-exchanged gold ions into account.

INTRODUCTION

The main goals of the Booster as the intermediate machine in NICA accelerator complex are the following [1]: to accumulate of $2{\cdot}10^9$ gold $^{197}Au^{31+}$ ions and to accelerate them from 3.2 MeV/u up to 578 MeV/u which is sufficient for their effective stripping to the bare gold nuclei state in the Booster-Nuclotron beam transport channel; forming of the required beam emittance with electron cooling system at energy 65 MeV/u; providing a fast extraction of the accelerated beam for its injection into the Nuclotron.

The Booster acceleration ramp is divided into four stages (see Figure 1): adiabatic ion capture into the separatrix during 0.02 s at the magnetic field plateau at injection energy of 3.2 MeV/u, ion acceleration up to 65 MeV/u during 0.4 s, electron cooling of $^{197}Au^{31+}$ ions during 1 s and ion acceleration up to energy 578 MeV/u during 1.3 s.

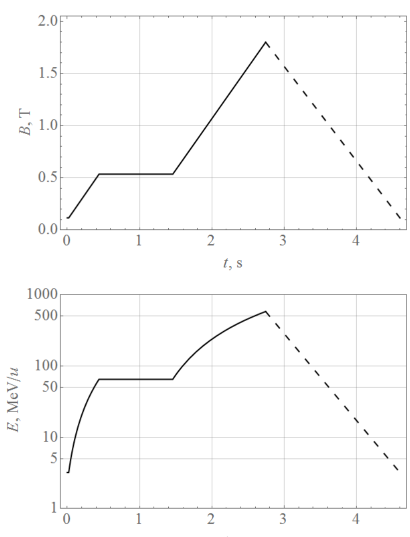

Figure 1: Booster time diagrams: magnetic field ramp (top) and acceleration ramp (bottom) of $^{197}Au^{31+}$ ions.

The vacuum system of the Booster divided into cold and warm parts. The surface of the cold part of the vacuum beam chamber has a temperature about 10 K, while the surface temperature of the warm part is close to room temperature 300 K. The cold part occupies most of the length of the Booster (circumference of the Booster is 210.96 m). Four warm straight part with a length about 7 m are present: injection (section 1); RF stations (section 2); extraction (section 3) and electron cooling system (section 4).

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BEAM LOSSES MECHANISMS AND PROBLEM STATEMENT

Beam losses mechanisms are well known and studied in several number papers ([2] and references therein). The charge-exchange of accelerated ions with molecules of the residual gas and the ionization of these molecules are the primary processes that result in the loss of multicharged ions in circular accelerators and affect the vacuum pressure. In the first case, recharged ions of a beam are deflected by the lattice dipoles and hit the walls of the accelerator chamber with a higher energy at a small angle. In the second case, the residual gas ions are accelerated by the beam potential and hit the walls with a low energy (about 30 eV for the Booster case) under nearly perpendicular angle to their surface. In both cases a large amount of desorbed molecules from the chamber walls go back the chamber, however, the first process is the dominant one [3].

The charge particles beam losses are characterized by the set of differential equations based on the results presented in [2]:

$$\begin{cases} \dfrac{dN_q}{dt} = -N_q \sum\limits_{\alpha} \left\langle \Gamma_{\alpha,q\to q-1} + \Gamma_{\alpha,q\to q+1} + \Gamma^{\text{Bethe}}_{\alpha,q\to q+1} \right\rangle, \\ N_q\big|_{t=0} = N_{q,0}, \\ V\dfrac{\partial n_\alpha}{\partial t} = \dfrac{\partial}{\partial z}\left(C_\alpha \dfrac{\partial n_\alpha}{\partial z}\right) - n_\alpha S_\alpha + \dfrac{Q_\alpha A}{k_B T} + \\ \qquad + N_q \left(\sum\limits_{\alpha} \left\langle \Gamma_{\alpha,q\to q-1} + \Gamma_{\alpha,q\to q+1} \right\rangle \eta_{\angle,\alpha} (1-\theta) + \right. \\ \qquad \left. + \sum\limits_{\alpha'} \left\langle \Gamma^{\text{Bethe}}_{\alpha',q\to q+1} \right\rangle \eta_{\perp,\alpha'/\alpha} \right), \\ n_\alpha\big|_{t=0} = n_{\alpha,0}, \quad n_\alpha\big|_{z=0} = n_\alpha\big|_{z=L}, \quad \dfrac{\partial n_\alpha}{\partial z}\Big|_{z=0} = \dfrac{\partial n_\alpha}{\partial z}\Big|_{z=L}. \end{cases} \tag{1}$$

Here N_q — beam intensity that depends on time t only; n_α — concentration *of* α-kind of residual gas that depends on the longitudinal coordinate z and time t; V — accelerator volume; $\eta_{\angle,\alpha}$ and $\eta_{\perp,\alpha/\alpha'}$ — desorption coefficients; θ — collimation efficiency; A — the Booster vacuum chamber surface area; Q_α — outgassing rate; S_α — pumping speed; k_B — Boltzmann constant; T — temperature; $\Gamma_{\alpha,q\to q+1}$ and $\Gamma_{\alpha,q\to q-1}$ — charge-exchange rate for one electron loss and one electron capture by beam ions due to interaction with residual gas atoms or molecules; $\Gamma^{\text{Bethe}}_{\alpha,q\to q+1}$ — ionization rate of residual gas atoms or molecules by beam ions; C_α — specific conductivity of the Booster vacuum chamber; L — the Booster circumference. The values V, A and S_α are

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taken per unit length. The angle brackets in the set (1) denote averaging over the longitudinal coordinate z.

The equations set (1) is supplemented by the following values: intensity at the initial time $N_{q,0}$, distributions of residual gas concentrations over the Booster ring at the initial time $n_{\alpha,0}$ and periodic boundary conditions for the residual gas concentration and its first-order derivative.

Note here that the charge-exchange rate is a product of the ion velocity, the cross section of the charge-exchange process (taken from [4]) and the residual gas concentration.

INITIAL DISTRIBUTION OF RESIDUAL GAS CONCENTRATIONS

The solution of the following system was used as the distribution of residual gas concentrations at the initial time:

$$\begin{cases} \dfrac{d}{dz}\left(C_\alpha \dfrac{dn_\alpha}{dz}\right) - n_\alpha S_\alpha + \dfrac{Q_\alpha A}{k_B T} = 0, \\ n_\alpha\big|_{z=0} = n_\alpha\big|_{z=L}, \quad \dfrac{\partial n_\alpha}{\partial z}\bigg|_{z=0} = \dfrac{\partial n_\alpha}{\partial z}\bigg|_{z=L}. \end{cases} \quad (2)$$

Let find the solution to the system (2) in two different cases: with actual pumps' layout around the Booster ring (pump is pinhole; speeds of the pumps are equal; pumps position at the centers of all intervals between the Booster lattice elements) and with averaged pumping speed in warm and cold Booster parts.

We found the solution of (3) over the Booster ring separately for warm and cold part. Let M is amount of parts of the simulated domain in case of actual pumps layout. This value includes amount of pumps, amount of additional conditions, such as defining the boundaries between warm and cold Booster parts and the periodical boundary conditions of the solution. In case of actual pumps layout for the equation set (3), we have:

$$\frac{d^2 n_{\alpha,i}}{dz^2} - \omega_{\alpha,i}^2 n_{\alpha,i} + \lambda_{\alpha,i} = 0, \quad i = \overline{1, M}. \quad (3)$$

The solution of the equation set (3) is as follows:

$$n_{\alpha,0} = \begin{cases} -\dfrac{\lambda_{\alpha,i}(z - z_{i-1})^2}{2} + A_{\alpha,i}(z - z_{i-1}) + B_{\alpha,i}, \\ z_{i-1} \le z < z_i, \quad i \in \text{warm}, \\ \dfrac{\lambda_{\alpha,i}}{\omega_{\alpha,i}^2} + A_{\alpha,i} e^{\omega_{\alpha,i}(z-z_{i-1})} + B_{\alpha,i} e^{-\omega_{\alpha,i}(z-z_{i-1})}, \\ z_{i-1} \le z < z_i, \quad i \in \text{cold}. \end{cases} \quad (4)$$

Here z_i are the coordinates of boundaries of the domain parts. The expressions for $\omega_{\alpha,i}$ and $\lambda_{\alpha,i}$ are given in (5).

$$\omega_{\alpha,i} = \sqrt{\frac{S_{\alpha,\text{cold}}}{C_{\alpha,i}}}, \quad \lambda_{\alpha,i} = \frac{Q_{\alpha,i} A}{k_B T_i C_{\alpha,i}}, \quad \Omega_{\alpha,i} = \sqrt{\frac{S_{\alpha,i}}{C_{\alpha,i}}}. \quad (5)$$

The constants $A_{\alpha,i}$ and $B_{\alpha,i}$ are defined by crosslinking conditions at the boundaries of the simulated domain which are given in (6).

$$\begin{cases} n_{\alpha,\text{warm/cold},i}\big|_{z=z_i-z_{i-1}} = n_{\alpha,\text{warm/cold},i+1}\big|_{z=0}, \\ \Omega_{\alpha,i}^2 \, n_{\alpha,\text{warm/cold},i}\big|_{z=z_i-z_{i-1}} = n'_{\alpha,\text{warm/cold},i+1}\big|_{z=0} - \\ -n'_{\alpha,\text{warm/cold},i}\big|_{z=z_i-z_{i-1}}, \; i = \overline{1, M-1}, \\ n_{\alpha,\text{cold},M}\big|_{z=z_M-z_{M-1}} = n_{\alpha,\text{warm},1}\big|_{z=0}, \; n'_{\alpha,\text{cold},M}\big|_{z=z_M-z_{M-1}} = n'_{\alpha,\text{warm},1}\big|_{z=0}. \end{cases} \quad (6)$$

In the second case with average pumping, we found the solutions of the system (2) in warm and cold parts separately:

$$\begin{cases} \dfrac{d^2 n_{\alpha,\text{warm}}}{dz^2} - \omega_{\alpha,\text{warm}}^2 n_{\alpha,\text{warm}} + \lambda_{\alpha,\text{warm}} = 0, \; n_{\alpha,\text{warm}}\big|_{z=0} = n_{\alpha,\text{cold}}\big|_{z=L_\text{cold}}, \\ \dfrac{d^2 n_{\alpha,\text{cold}}}{dz^2} - \omega_{\alpha,\text{cold}}^2 n_{\alpha,\text{cold}} + \lambda_{\alpha,\text{cold}} = 0, \; n_{\alpha,\text{cold}}\big|_{z=0} = n_{\alpha,\text{warm}}\big|_{z=L_\text{warm}}. \end{cases} \quad (7)$$

Here expressions for $\omega_{\alpha,\text{warm/cold}}$ and $\lambda_{\alpha,\text{warm/cold}}$ are given in (10) and $L_\text{warm/cold}$ — length of warm and cold Booster parts that were assumed equal to 7 and 98.48 m. The solution of the system (7) is as follows:

$$\begin{gathered} n_{\alpha,\text{warm/cold}} = \frac{\lambda_{\alpha,\text{warm/cold}}}{\omega_{\alpha,\text{warm/cold}}^2} + A_{\alpha,\text{warm/cold}} e^{\omega_{\alpha,\text{warm/cold}} z} + B_{\alpha,\text{warm/cold}} e^{-\omega_{\alpha,\text{warm/cold}} z}, \\ \omega_{\alpha,\text{warm/cold}} = \sqrt{\frac{s_{\alpha,\text{warm/cold}}}{C_{\alpha,\text{warm/cold}}}}, \quad \lambda_{\alpha,\text{warm/cold}} = \frac{Q_{\alpha,\text{warm/cold}} A}{k_B T_\text{warm/cold} C_{\alpha,\text{warm/cold}}}. \end{gathered} \quad (8)$$

Here the constants $A_{\alpha,\text{warm/cold}}$ and $B_{\alpha,\text{warm/cold}}$ are defined by crosslinking conditions (7).

The relation between pumping parameters at the warm and cold parts in the averaged model and the same parameters of the model with actual pumps layout is as follows:

$$s_{\alpha,\text{warm}} = \frac{\sum_{i \in \text{warm}} S_{\alpha,i}}{L_\text{warm}}, \quad s_{\alpha,\text{cold}} = S_{\alpha,\text{cold}} + \frac{\sum_{i \in \text{cold}} S_{\alpha,i}}{L_\text{cold}}. \quad (9)$$

Here $C_{\alpha,\text{warm/cold}}$, $Q_{\alpha,\text{warm/cold}}$, $s_{\alpha,\text{warm/cold}}$ and $T_\text{warm/cold}$ define the specific conductivity, outgassing rate, average pumping speed and temperature in warm and cold Booster parts (see on poster Figure 2). Also note here that the values with the second lower index warm/cold or i like C_α, Q_α, s_α, S_α and T_i or $T_\text{warm/cold}$ in (4), (5) and (8) are the constant and determined by the position, i.e. warm/cold or index i.

Table 1: Average Pumping Speed, Outgassing Rate And Desorption Coefficients (taken from [5])

	H_2	CH_4	CO	CO_2
s_warm, $\text{l·s}^{-1}\text{·m}^{-1}$	0.46	0.56	5.76	6.25
s_cold, $\text{l·s}^{-1}\text{·m}^{-1}$	2.41	145.81	114.26	74.94
Q_warm, 10^{-12} mbar·l·s^{-1}·cm^{-2}	0.025	0.015	0.018	0.014
Q_cold, 10^{-12} mbar·l·s^{-1}·cm^{-2}	0.003	0.001	0.001	0.001
$\eta_{\angle,\text{warm}}(^{197}Au^{31+})$	150	5	1000	250
$\eta_{\angle,\text{cold}}(^{197}Au^{31+})$	1500	50	10000	2500
$\eta_{\perp,\text{warm}}(H_2^+)$	0.54	0.54	0.54	0.54
$\eta_{\perp,\text{warm}}(CH_4^+)$	0.04	0.05	0.07	0.11
$\eta_{\perp,\text{warm}}(CO^+)$	0.25	0.29	0.29	0.33
$\eta_{\perp,\text{warm}}(CO_2^+)$	0.14	0.14	0.14	0.14
$\eta_{\perp,\text{cold}}(H_2^+)$	0.33	0.33	0.33	0.33
$\eta_{\perp,\text{cold}}(CH_4^+)$	0.02	0.03	0.04	0.07
$\eta_{\perp,\text{cold}}(CO^+)$	0.15	0.17	0.17	0.2
$\eta_{\perp,\text{cold}}(CO_2^+)$	0.09	0.09	0.09	0.09

For the specific conductivity C_α of vacuum chamber the Knudsen formula was used [6]:

$$C_\alpha = \frac{4}{3}\frac{u_\alpha V^2}{A}.$$

Here u_α — mean particles' speed of α-kind residual gas component. This formula is more general since it takes into account the distribution function of the residual gas atoms and molecules and varying the Booster vacuum chamber aperture.

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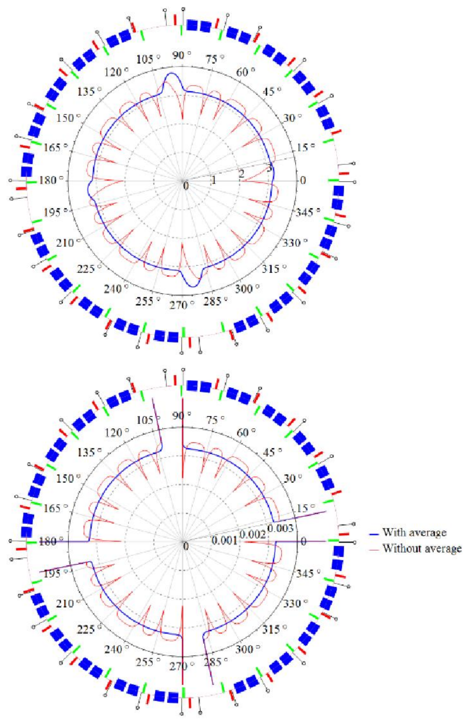

Figure 2: Total gas concentration in 10^6 cm^{-3} (top) and total static pressure in nTorr (bottom).

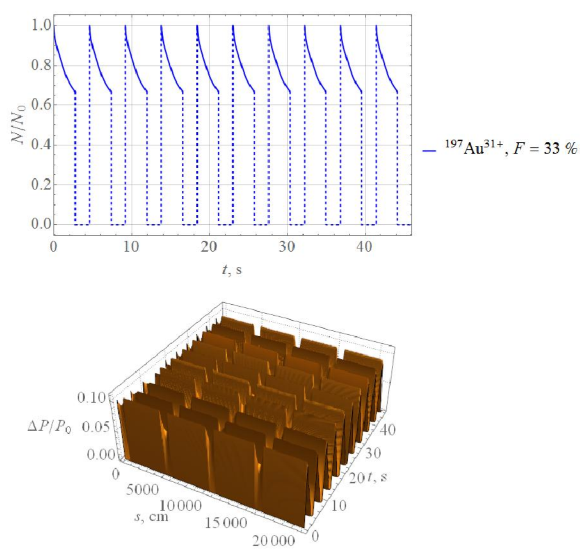

Figure 3: Time dependence of gold $^{197}Au^{31+}$ ion beam losses (top) and total dynamic residual gas pressure rises (bottom). Beam losses F are about 33% and residual gas pressure rise ΔP is not more 10% for average pressure level in the Booster vacuum chamber about 0.01 nTorr.

CALCULATION RESULTS

The solution of non-stationary problem (1) for the Booster magnetic cycle (see Figure 1) with the initial stationary distribution (see Figure 2) and parameters' list for average pumping speed, outgassing rates and desorption coefficients given in the Table 1 is shown in Figure 3. The residual gas composition is taken as follows: H_2, CH_4, CO and CO_2; initial $^{197}Au^{31+}$ ions beam intensity was $2\cdot10^9$; collimation efficiency was taken not more that 35%.

Two curves represented on Figure 2 correspond to (4) solution in case of actual pumps layout (2) and to (8) solution in case of average pumping speed around the Booster ring (7). The relation (9) between parameters of the problems (3) and (7) is taken into account. The Booster lattice and pumps layout are also shown on Figure 3.

CONCLUSION

The mathematical model of gold $^{197}Au^{31+}$ ions beam losses calculation due to interaction with residual gas atoms and molecules is given. The presented results are taken the ion stimulated desorption from the Booster vacuum cold surface and collimation of charge-exchanged gold ions into account.

The analytical solutions of the stationary problem for residual gas concentrations in the Booster vacuum chamber in case of two different problem statements (actual pumps layout and average over the Booster ring pumping speed) are given.

It was shown that for the values of pumping speed averaged over the Booster ring, outgassing rates and desorption coefficients in the warm and cold Booster parts close to the project expected values [1], the gold $^{197}Au^{31+}$ ions beam losses are of about 33% that corresponds to average residual gas pressure in the Booster vacuum chamber about 0.01 nTorr.

Note that in the presented simulation the residual gas composition in the warm Booster part was about 90% H_2 and about 10% totally of CH_4, CO and CO_2. The residual gas composition was approximately 100% H_2 in the cold Booster part. In general case, the proposed mathematical model provides arbitrary residual gas composition to be simulated.

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