ION TRAPPING STUDY IN eRHIC*

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Abstract

The ion trapping effect is an important beam dynamics issue in energy recovery linac(ERL). The ionized residue gas molecules can accumulate at the vicinity of the electron beam path and deteriorate the quality of the electron beam. In this paper, we present calculation results to address this issue in eRHIC and find best beam pattern to eliminate this effect.

INTRODUCTION

eRHIC is the future electron ion collider(EIC), which collides 5GeV to 30GeV electron beam from a new electron accelerator with the ion beam from existing RHIC ring. The electron accelerator adopts a multi-pass ERL, which contains 6 passes with 2 linacs per pass.

The electron impacted ionization effect needs attention to ensure the quality of the electron beam. The high energy electrons ionize the residue gas in beam pipe. These ions may accumulate and are 'trapped' near the axis of the pipe where the electron beam passes, due to the interaction with the electron beam. The concentration of the ion may produce noticeable space charge field that affects the electron beam and neutralize the electron beam in the linacs.

In the paper, we start with cross section of the ionization process and determine the accumulation time, which are followed by the calculation to determine the criteria of the ion trapping. The ion trapping effect is determined by the longitudinal configuration of the electron bunches. The effect can be reduced or mitigate by some proper electron beam patterns. We will present these patterns with a linearized model.

ION GENERATION

To evaluate the accumulation time of different ion species, we need to calculate the cross sections of electron impacted ionization. A useful model, Binary-Encounter-Bethe (BEB), was developed in 1994[1].

$$\sigma_{BEB} = \frac{S}{t+u+1}\left[\frac{\ln t}{2}\left(1-\frac{1}{t^2}\right)+1-\frac{1}{t}-\frac{\ln t}{t+1}\right] \tag{1}$$

where $t = T/B$ and $u = U/B$ are the normalized incident and kinetic energy, $S = 4\pi a_0^2 N \left(R/B\right)^2$. The parameters required are the binding energy B , orbital kinetic energy U and incident electron energy T, as well as the Bohr radius a_0 and Rydberg energy $R = 13.6$ eV.

Table 1: Ionization Cross Sections for Some Gas Molecules

Residue gas	Parameters in Eq.3		Cross section $[\times 10^{-18}\text{cm}^2]$	
	M^2	C	0.1 GeV	4 GeV
H_2	0.70	8.1	0.28	0.37
H_2O	3.2	32	1.2	1.6
CO_2	5.8	56	2.1	2.9
N_2	3.7	35	1.3	1.8
CO	3.7	35	1.3	1.8
CH_4	4.2	42	1.5	2.1
O_2	4.2	39	1.4	2.1

Started much earlier, many experiments was performed to measure the cross section of electron impacted ionization. We are interested in the number of different species residue gases interacting with high energy electrons. A simpler model carried out in [2] gives:

$$\sigma = 4\pi\left(\frac{\hbar}{mc\beta}\right)^2\left[M^2\left(2\ln\left(\beta\gamma\right)-1\right)+C\right] \tag{2}$$

where M and C can be determined from experiments. For high energy electrons ($\beta \sim 1$), it can be simplified as:

$$\sigma = 1.874\times 10^{-20}\text{cm}^2\left[M^2\left(2\ln\gamma-1\right)+C\right] \tag{3}$$

In Table 1, the cross sections of electron impacted ionization for major residue gases are calculated using Equation 3. Except for hydrogen, other common gases has similar values around $2\times 10^{-18}\text{cm}^{-2}$. Hydrogen 's cross section is about one order lower.

The ionization rate can be calculated from the given cross section σ_i by

$$\frac{d\lambda_i}{dt} = \sigma_i n_g I_{inc} \tag{4}$$

where λ_i is the line density of generated ion, n_g is the particle density of residue gas and I_{inc} is the current of the incident electron beam. The residue gas density can be obtained from the gas pressure, $n_g = P/RT$, where P is the partial pressure of the gas, T is the temperature. Usually the time between successive bunch is much shorter than the typical time for ion accumulation, therefore we can use the average current in Eq. 4 to evaluate the increment speed. In multi-pass (p passes) ERL, there are $2p$ bunches in linac so that Eq. 4 becomes:

$$\frac{d\lambda_i}{dt} = 2p\sigma_i n_g I_e \tag{5}$$

When the line density of accumulating ions reaches the density of the electron beam, no acceleration can continue since the whole system is neutralized. The neutralization time can be easily estimated from Eq.4, $\tau_i = 1/(\sigma_i n_g c)$.

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ION TRAPPING IN LINAC, MODEL

For a p-path ERL, the ionized gas molecules meet $2p$ electron bunches of different energies in one repetition period. This period is defined by the collision event frequency $T = 1/f_c$. The RF frequency of ERL linacs must be certain integer $l \geq 2p$ harmonics of the event frequency f_c. Therefore, the ERL linacs forms l accelerating phases and l decelerating phases, which accommodate p energy-increasing electron bunches and p energy-decreasing bunches respectively. Theoretically there is $l \times C(l, p)$ different longitudinal patterns, where $C(a, b)$ is the binomial coefficient. The specific longitudinal partition is determined by the path length of the energy recovery paths with the requirement that the i^{th} low energy passes have $L = m_i \lambda$ and highest energy pass has $L = (n + 1/2)\lambda$, where λ is the wavelength of the ERL Cavity. Practically, in high energy ERL, the low energy passes are design to be same length to reduce the complexity, i.e. $m_i = m$, because the time of flight of the electron beams are identical. Under this condition, the possible number of longitudinal patterns reduces to l^2, with two free integer parameters m and n within the ranges $[0, l-1]$.

In the repetitive time window T, the $2p$ electron bunches reside at $d_i \lambda / c$ with

$$\begin{aligned} d_i &= \{0, m, \ldots, (p-1)m, (p-1)m + n \\ &\quad , \ldots, (2p-1)m + n\} \bmod l \end{aligned} \tag{6}$$

Therefore, the electron beam current in the time window is

$$I(t) = \sum_i \frac{N_e}{\sqrt{2\pi}\sigma_t} \exp\left[-\frac{(t - d_i\lambda/c)^2}{2\sigma_t^2}\right] \tag{7}$$

The ionized gas molecule experiences an E-M field that generated by the electron bunch. The linear component of the force gives

$$F = -\frac{e^2 n_e}{2\pi\epsilon_0\sigma^2(E)} \begin{pmatrix} x \\ y \end{pmatrix} \tag{8}$$

where n_e is the electron bunch line density. $\sigma(E)$ is the transverse beam size, which is function of the electron beam energy. Here we assume the electron beam is round in the cavity and the molecule only lose one electron. The negative sign indicates the force is always attractive.

We can model the ion motion by $2 \times 2p$ matrices, which contains $2p$ focusing matrices and $2p$ drift space matrices.

$$M_f = \begin{pmatrix} 1 & 0 \\ -N_e r_i/\sigma^2(E) & 1 \end{pmatrix} \tag{9}$$

$$M_d = \begin{pmatrix} 1 & (d_{i+1} - d_i)\lambda \\ 0 & 1 \end{pmatrix} \tag{10}$$

where r_i is the classical radius of the ion. One can extend equation 9 and 10 to consider that there is existing ion accumulation and electron beam has been partially neutralized. However, here we consider the strictest case.

Table 2: Parameter of eRHIC

Parameters	Values
Collision frequency f_c (MHz)	14.08
ERL RF frequency (MHz)	704
Number of passes p	6
Number of bucket l	50
Number of linac per pass	2
Top energy (GeV)	30
Injection energy (GeV)	0.6
Normalized emittance (m-rad)	20×10^{-6}
Length of linac (m)	200

By multiplying the $4p$ matrices, we can determine the ion stability from the eigenvalues. If the eigenvalues are real, the ion is not stable near the beam pipe axis and will be cleared automatically.

CALCULATION RESULT

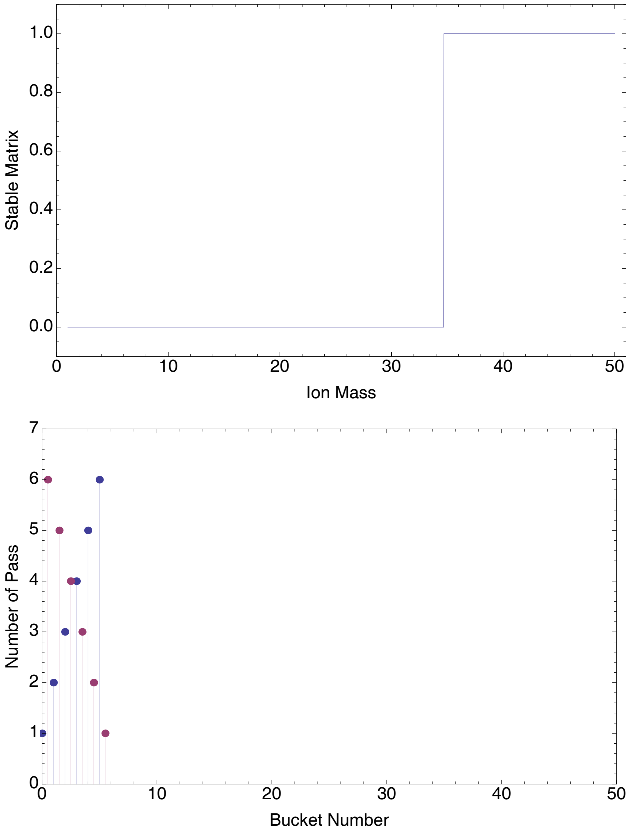

Figure 1: The optimized pattern for clearing the ion($m = 1$, $n = 44$). In the top figure, the ion stability is shown as function of the ion mass. In the bottom figure, the blue dots and red dots represent the accelerating and decelerating bunch respectively.

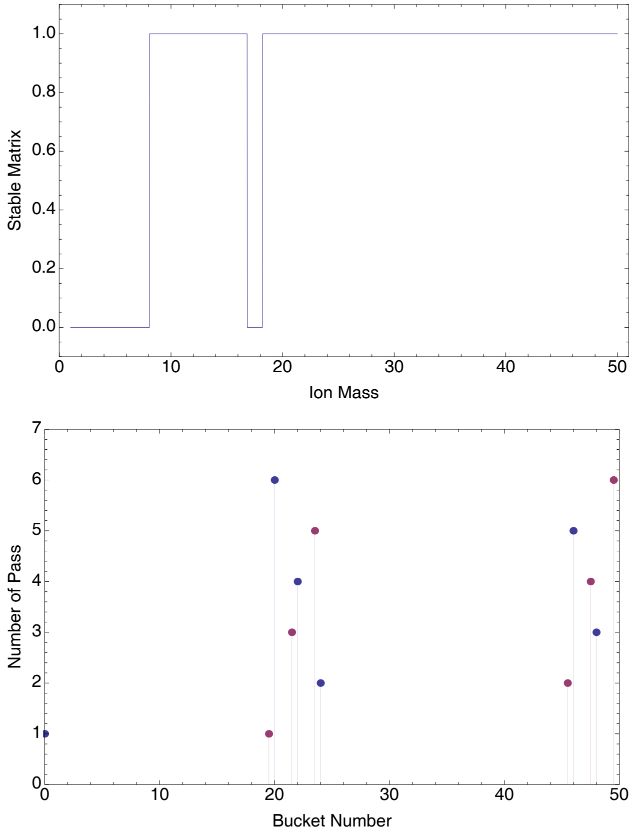

Figure 2: A realistic pattern that fit the ERL in the existing tunnel of RHIC ($m = 24$, $n = 29$).

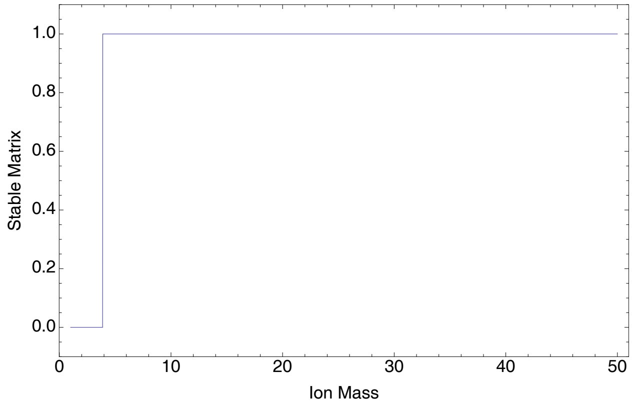

Figure 3: Ion clearing at $s = 40$ m from the end of the linac, for the realistic case in figure 2.

Table 2 lists the related parameter of eRHIC[3] . Since there are no quadrupoles between RF cavities, the beta function in linacs with high energy approximation has the same form as in drift space.

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \tag{11}$$

where β^* is the beta function at middle point of the linac. When $\beta^* = L_{linac}/\sqrt{12}$, the average beta function in linac reaches its minimum and the beam size in this calculation is attained. We first consider the position at the mid-point of the linac, where the beam-size of the electron beam for all energies are minimum.

Figure 1 shows an ideal longitudinal pattern of the electron beam to prevent ion accumulation. All bunches are grouped as close as possible to over focus the ion beam and leave longest free space for the ion traveling to the pipe. Any ion mass less than $A = 34$ won't be accumulate along the electron beam path and be cleared automatically. However, if we consider the realistic constrains such as fitting the ERL in the exist RHIC tunnel, the pass length can't adjust $l\lambda = 20$ m. Therefore m and n are only allow to choose from a much smaller range. A realistic case is shown in figure 2 to optimize the ion clearing with the constrains. More ion species tend to be trapped since the focusing strength is weak and the drift space between bunches is shorter, compared with the ideal pattern.

However, in the superconducting RF cavity, the temperature of operation is below 4.2K, where all ion species freeze except helium. In both cases, helium molecules will be cleared.

When we consider other positions in linac, the ion clearing effect is weakened due to large electron beam size is observed. In realistic case, shown in figure 2, the ion at $s = 40$ m from the end of the linac is shown in figure 3, the helium's ion mass in at margin of the unstable matrix. Therefore, the helium ions will be trapped in both 40m ends of the 200m linac. Other ion clearing method is required such as the electro-static clearing electrodes.

CONCLUSION

We present the linearized calculation on the ion motion in the cavity of multi-pass ERL and determine the stability of the ion motion from the results. We conclude that the ionized molecules won't accumulated in eRHIC linacs except both 40 ends. Electro-static clearing electrodes should be installed in those regions to remove the ions from accumulation.

REFERENCES

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