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Beam Loss and Vacuum Requirement in Heavy Ion Accelerator

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1. Introduction

It is inevitable that ion beams traveled in the beam tube of heavy ion accelerators interact with residual gas molecules, which may result in a nontrivial loss of the available beam power. A large beam loss cannot be tolerated not only in the aspect of the beam economy itself, but also because of the induced radioactivity due to activation of surrounding structures.

Tolerable beam losses can be possibly defined to allow hands-on maintenance of accelerator components without unreasonable constraints after a typical operating period of an accelerator followed by a reasonable cooling down time, then dose-rate levels should be below 1 mSv/h (measured at 30 cm apart from the component surface after100 days irradiation and 4 hours cooling). This corresponds to the linear beam loss of about 1 W/m along the enclosure of the 1 GeV proton beam. The heavier ion induces the lower activation, and then the power loss limit can be much increased. For example, 40 W/m is suggested as the limit for 1 GeV U ions. [1]

The beam loss limit may be given by so called the vacuum instability, which is usually much lower than that determined by allowable radioactivity. For example, the power loss limit of 40 W/m for the U ion can generate roughly a pressure rise of ~1.7x 10^{-7} mbar, for a 200 MeV beam energy, a pumping rate of 100 L/s/m, and a desorption yield of 50,000, which is intolerable in any sense. An excessive ion loss and gas desorption can lead to a large pressure rise which again induces additional ion losses, and results in a vacuum instability.

In this report, calculation procedures to establish the vacuum requirements of RAON as a model heavy ion accelerator are proposed and the results are discussed.

2. Beam Interaction with Residual Gas

Interactions of ions and residual gas molecules are categorized mainly by charge exchange and ionization processes, and the charge exchange is again divided into electron capture ($X^{q+} + A \rightarrow X^{(q-k)+} + A^{k+}$) and electron loss ($X^{q+} + A \rightarrow X^{(q+m)+} + A^{*} + me^{-}$) of projectile ions.

A generalized formula for the cross section of electron capture is expressed as [2-5];

$$\sigma_c = f(E)\frac{1.1\times 10^{-8}}{\tilde{E}}\frac{q^{0.5}}{Z_T}[1-e^{0.037\tilde{E}^{2.2}}][1-e^{-2.44\times 10^{-5}\tilde{E}^{2.6}}]\ (E < 100MeV)$$

$$\tilde{E} = \frac{E}{Z_T^{1.25}q^{0.7}}$$

$$\sigma_c(E\rightarrow 0) \approx 10^{-15}\frac{q}{(I_T/13.606)^{1.5}}$$

$$\sigma_c = 21+10.6(6.6+8.7\times 10^{-102}e^{q/0.39})(18+6.3e^{Z_T/3.76})e^{-E/95}\ (E \geq 100MeV)$$

σ_c: Electron capture cross-section [cm^2]
E: Projectile energy [keV/u]
q: Projectile charge state
Z_T: Target nuclear charge
I_T: Ionization potential of target atom [eV]
f(E): Correction factor for low-energy range and multiple charge exchange events

The cross section of the electron loss has the form as followed [6];

$$\sigma_l = 0.88\times 10^{-16}(Z_T+1)^2\frac{u}{u^2+3.5}\left(\frac{13.606}{I_p}\right)^{1+0.01q}\left[4+\frac{1.31}{n_0}ln(4u+1)\right]$$

$$u = \frac{(137\beta)^2}{I_p/13.606}$$

$$\sigma_{l,\max}(u\sim 2) \approx 10^{-16}(Z_T+1)^2(13.606/I_p)^{0.01q}$$

σ_ℓ: Electron loss cross-section [cm^2]
β: Relativistic factor (v/C)
n_0: Principal quantum number of outermost shell of projectile ion
I_p: Ionization potential of projectile ion [eV]

Lastly, ionization of the gas molecules by projectile ions has the cross section of following form [7-9];

$$\sigma_I = q^2 e^{-\lambda q(137/\beta)^2}\sigma_{Bethe}$$

$$\sigma_{Bethe} = 1.874\times 10^{-20}(M^2x_1+Cx_2)$$

$$x_1 = \beta^{-2}\ln\frac{\beta}{1-\beta^2}-1,\ x_2 = \beta^{-2}$$

σ_I: Target ionization cross-section [cm^2]
M, C, λ: Empirical characteristic constants for target molecules (for example, 0.7/8.12/1 for Hydrogen)

The linear ion loss rate [ions/m/s], assuming that any single or multiple charge exchange events lead to a permanent loss, is obtained in the following sequence;

1) Ion flux: $\Phi[ions/m^2/s]=I[pmA]x10^{-6}/e/A_{beam}$
2) Specific Loss Rate[$ions/m^3/s$]: $L_s=d\Phi/dx=\Phi\sum n_g\sigma_i$
3) Unit Length Loss Rate[ions/m/s]: $L_u=L_s \times A_{beam}$
4) Unit Desorption Rate[molecules/m/s]: $Q_{SD}=\eta L_u$
5) Pressure Rise: ΔP [mbar at 20℃]=$Q_{SD}/2.5x10^{19}/S_U$

n_g: density of gas molecules [$/cm^3$]
η: on stimulated desorption yield [molecules/ion]
S_U: pumping speed per unit length [L/s/m]

3. Pressure Rise Estimation

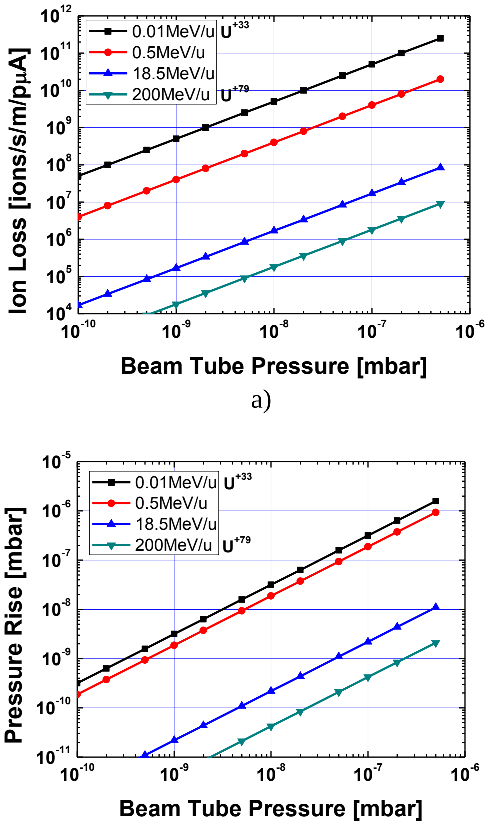
The ion losses and the resultant pressure rises calculated for U^{33+} and U^{+79} ions depending on the base pressure along accelerating stages of RAON are summarized as Figure 1. It is recognized that the pressure rise in the low energy section up to MEBT cannot be neglected at least in this estimation.

The criterion for suppressing the vacuum instability is generally given by following inequality equation;

$$\Delta P/P=\sigma_{Loss}I_b\eta_{desorp}/(kT_{gas}eZ_{ion}S_{eff})<1$$

It is noteworthy that merely reducing the base pressure cannot satisfy above relation because the pressure rise ΔP is generally proportional to the base pressure P, and the ratio ΔP/P is still unchanged.

The reasonable solution to effectively satisfy the relation is lowering the ion stimulated gas desorption (η_{desorp}) by well conditioning of the wall and increasing the effective local pumping speed (S_{eff}) around desorption site. And the machine should be carefully operated step by step with a gradually raised beam current for slow aging of the wall to avoid an abrupt huge gas desorption.



a)

b)

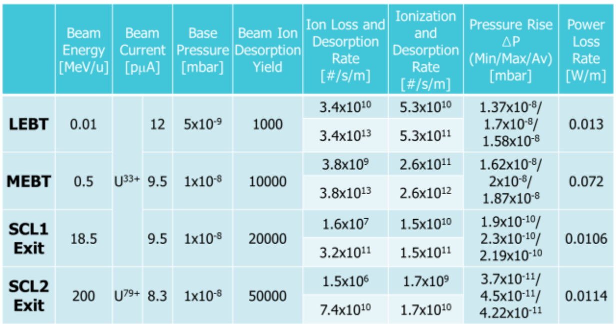
Fig. 1. a) The ion loss and b) consequent pressure rise for U^{33+} and U^{79+} ions under a model gas composition of H_2O: 60%, H_2: 15%, CH_4: 10%, CO: 10%, Ar: 5%.

4. Conclusions

The pressure rise due to ion losses in RAON heavy ion accelerator has been estimated using some fitted cross sections to be lower enough in most accelerating section not to induce a vacuum instability except in the injection parts up to MEBT. (refer to Table 1)

However, it is safe to say that the situation doesn't seem that severe because the desorption yield, of which data is much scattered with large uncertainties, was assumed much conservatively, and can be diminished dramatically by proper wall treatments and careful beam conditionings. Localizing the beam interaction with the wall into specified elements like a collimator may also be helpful to mitigate the pressure rise by arranging proper pumping sites.

Table 1. Summary of pressure rise estimation due to beam loss in RAON.



	Beam Energy [MeV/u]	Beam Current [pμA]		Base Pressure [mbar]	Beam Ion Desorption Yield	Ion Loss and Desorption Rate [#/s/m]	Ionization and Desorption Rate [#/s/m]	Pressure Rise ΔP (Min/Max/Av) [mbar]	Power Loss Rate [W/m]
LEBT	0.01	U^{33+}	12	$5x10^{-9}$	1000	$3.4x10^{10}$ $3.4x10^{13}$	$5.3x10^{10}$ $5.3x10^{11}$	$1.37x10^{-8}$/ $1.7x10^{-8}$/ $1.58x10^{-8}$	0.013
MEBT	0.5		9.5	$1x10^{-8}$	10000	$3.8x10^{9}$ $3.8x10^{13}$	$2.6x10^{11}$ $2.6x10^{12}$	$1.62x10^{-8}$/ $2x10^{-8}$/ $1.87x10^{-8}$	0.072
SCL1 Exit	18.5		9.5	$1x10^{-8}$	20000	$1.6x10^{7}$ $3.2x10^{11}$	$1.5x10^{10}$ $1.5x10^{11}$	$1.9x10^{-10}$/ $2.3x10^{-10}$/ $2.19x10^{-10}$	0.0106
SCL2 Exit	200	U^{79+}	8.3	$1x10^{-8}$	50000	$1.5x10^{6}$ $7.4x10^{10}$	$1.7x10^{9}$ $1.7x10^{10}$	$3.7x10^{-11}$/ $4.5x10^{-11}$/ $4.22x10^{-11}$	0.0114

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