BEAM INDUCED TRANSIENT VACUUM INSTABILITY IN H- BEAM*

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Abstract

When high current beam is transported through a vacuum channel, vacuum instability can develop due to desorption caused by ion/electron bombardment of the walls. In case of pulsed beam one can have situation when stability conditions are satisfied in average, while violated during the pulse. This effect can cause additional losses for H- beams due to stripping on the tail of the pulse. Expression for instability threshold is derived and estimations are done for the SNS MEBT beam parameters.

1 INTRODUCTION

Charged particles of a beam passing through a vacuum channel collide with atoms of residual gas thus producing electron – ion pairs, which can be accelerated by coulomb field of the beam toward the wall of the vacuum chamber. Impact energy of the secondary particles can be in the range of hundreds volts to several kilovolts, which is very efficient for desorbing gas molecules from the wall. The beam can ionize desorbed molecules as well and vacuum instability can develop. This phenomenon is well known from storage rings experience [1] and can be overcome by providing sufficiently large pumping speed and/or by reducing desorption coefficient.

In case of high intensity pulsed beam there are to distinct stages:

1. Beam is on. Gas is being desorbed from the walls.
2. Beam is off. Gas is being pumped from the chamber.

If the vacuum channel has small transverse aperture compared to longitudinal distance between pumping holes, which is common configuration in real accelerators, then desorbed secondary particles do not have enough time to reach pump for the beam pulse duration but they have enough time to bounce several times between transverse walls of the chamber, thus giving rise to instant pressure of the residual gas due to multiplication. The released gas is pumped out during the stage 2 between the beam pulses. As a result, pressure of the residual gas exhibits sharp spikes synchronized with the beam. If beam duty factor is of the order of several percent, then average effect on vacuum system can be negligible and even immeasurable due to slow response of the common vacuum gauges. But it can be of significant importance for H- beam because H- stripping on the residual gas depends on instant pressure and can lead to considerable stripping losses on the trailing edge of the beam.

2 IONIZATION CROSS-SECTION

Cross section for collision ionization depends on gas properties and velocity of ionizing particle. It can be calculated using Bethe-Bloch energy loss formulae or found in reference tables. Tabulated experimental data of energy losses are more reliable at low energy and were used in the following calculations [2]. Cross section σ_i can be derived from energy loss per unit length:

$$\sigma_i = \frac{dE}{dx} \cdot \frac{M}{\varepsilon_i} \quad ,$$

where $\frac{dE}{dx}$ is energy loss per $\frac{g}{cm^2}$, M is mass of the ionized atom, ε_i is energy of ion pair creation. Then:

$$\sigma_i[cm^2] = 1.66 \cdot 10^{-18} \cdot \frac{dE}{dx}\left[\frac{MeV \cdot cm^2}{g}\right] \cdot \frac{A[a.u.]}{\varepsilon_i[eV]}.$$

In nitrogen $\frac{dE}{dx} \approx 120 \frac{MeV \cdot cm^2}{g}$

for 2.5MeV H^-, A=14, $\varepsilon_i \approx 15eV$, then

$$\sigma_i \approx 2 \cdot 10^{-16} cm^2 .$$

3 DESORPTION RATE AND AVERAGE VACUUM LOAD

Number of ion-electron pairs created by N_b beam particles per second per unit length is

$$N_i = \frac{I_b}{e} \sigma_i n_r ,$$

where I_b is beam current, n_r is density of residual gas, e is electron charge. Each incident particle produces η of desorbed molecules. Then total number of released molecules per second per unit length is

$$N_d = \eta \frac{I_b}{e} \sigma_i n_r \ ,$$

then

$$PV = kTN_d = \eta \frac{I_b}{e} \sigma_i n_r kT \ .$$

Corresponding additional outgassing in practical vacuum units is:

$$Q[\frac{torr \cdot l}{cm \cdot c}] = 6.25 \cdot 10^{10} \cdot \eta \, I_b[mA] \sigma_i [cm^2] P[torr].$$

For the design MEBT parameters of I_b=2mA, $P = 5 \cdot 10^{-7}$ torr, $\eta \approx 5$ (unbaked SS [3]), outgassing rate is

$$Q \approx 1.25 \cdot 10^{-10} \, \frac{torr \cdot l}{cm \cdot c}.$$

For the total MEBT length of $400cm$ it gives $5 \cdot 10^{-8} \, \frac{torr \cdot l}{c}$ of additional load, which is negligible for the present vacuum system.

4 TRANSIENT VACUUM LOAD

Molecules desorbed from the wall have thermal velocities $v = \sqrt{\frac{2kT}{\pi m}}$ that are about $2.4 \cdot 10^4 \, \frac{cm}{s}$ for nitrogen at room temperature. Molecule can travel about 24cm during the beam pulse and barely can reach vacuum pump. But they can bounce several times between chamber walls for that time, desorbing gas molecules. Therefore we can neglect pumping and calculate how residual gas density varies during the beam passage. Variation of the gas density can be obtained from the above formulae for number of released particles per second per unit length:

$$dn_r = \frac{N_d}{\pi a^2} dt = \eta \frac{I_b}{e} \frac{\sigma_i n_r}{\pi a^2} dt \, ,$$

then solution for gas density n_r is

$$n_r = n_{r0} e^{\alpha \cdot t} \, ,$$

where $\alpha = \eta \frac{I_b}{e} \frac{\sigma_i}{\pi a^2}$. At the end of the beam pulse pressure rises by $e^{\alpha \cdot \tau}$, where τ is the beam pulse duration. Corresponding increase of relative integral stripping losses is

$$R = \frac{\int_0^\tau n_r(t)dt - \int_0^\tau n_{r0} dt}{\int_0^\tau n_{r0} dt} = \frac{e^{\alpha\tau} - 1 - \alpha\tau}{\alpha\tau}$$

Assuming $R << 1$, $R \approx \frac{\alpha\tau}{2}$. And corresponding limit for the beam current is

$$I_b << \frac{\pi e a^2}{\eta \sigma_i \tau} \approx \frac{5}{\eta} \frac{a^2[cm^2]}{\sigma \; [10^{-16} cm^2]} \frac{1[A]}{\tau[ms]} \, .$$

For the SNS MEBT $a = 1.5cm$, $\tau = 1ms$, resulting beam current limit is of about 1A, which is 20 times larger then the design beam current of 56mA and provides good safety margin.

5 CONCLUSION

Beam-induced gas desorption can cause additional stripping losses in H- high power beams. Estimation shows negligible effect for the SNS MEBT parameters with good safety margin. Expression for current limit derived above can be used to identify potentially dangerous places: low energy channels (due to increase of ionization cross section), small aperture channels such as drift tubes in DTL at low energy, long beam pulses.

6 REFERENCES

[1] Handbook of Accelerator Physics and Engineering, 1998, 225-227.
[2] http://physics.nist.gov/cgi-bin/Star/ap_table.pl

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