ELECTRON-IMPACT DESORPTION OF THE RHIC BEAM PIPES*

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Abstract

This paper describes the pressure evolution produced by an electron-impact desorption in the Relativistic Heavy Ion Collider (RHIC) beam pipes. The pressure crucially depends on the electron induced molecular desorption coefficient of the beam pipe material, which provides the number of molecules released when an electron hits its surface. This coefficient is inferred from electron detector and pressure gauge signals. The evolution of the electron-impact desorption coefficient after weeks of electron bombardment is shown.

INTRODUCTION

Bunches are injected into RHIC one by one up to a maximum of 110. This allows to study the evolution of the electron flux and pressure rise due to an electron cloud formation as the beam bunches are being injected. Injection of 110 bunches lasts at least 30 seconds. The user can halt the injection at any time for as long as it is necessary. The pressure rises produced by an electron cloud depend on the electron-impact desorption coefficient η, which provides the number of molecules released when an electron hits its surface. This coefficient changes as a function of the material, energy of electrons or surface conditioning. In the following, we analyze the experimental data taken with the RHIC electron detectors as well as vacuum pressure gauges to infer this coefficient and give its evolution after weeks of electron bombardment.

The pressure P at a vacuum pump location due to an electron cloud in a periodic structure with vacuum pumps of pumping speed $2S$ spaced by the distance $2L$ is proportional to the time averaged electron flux to the wall, $\langle dI/dl \rangle_\tau$ [1]:

$$P = P_0 + \eta \frac{kT}{e} \frac{L}{S} \left\langle \frac{dI}{dl} \right\rangle_\tau , \quad (1)$$

where P_0 is the static pressure, e is the absolute value of the electron charge, k is Boltzman's constant, T is the temperature. It is convenient to use the average bunch-to-bunch electron flux expressed in terms of the bunch number m,

$$\phi(m) = \frac{1}{s_b} \int_{ms_b}^{(m+1)s_b} \frac{dI(t)}{dl} dt \quad (2)$$

where s_b is the time between bunches.

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If M is the total number of possible bunches in a machine revolution, then

$$\langle dI/dl \rangle_\tau = \frac{1}{\tau} \int_0^\tau \frac{dI(t)}{dl} dt = \frac{1}{M} \sum_{m=0}^{M-1} \phi(m) , \quad (3)$$

and Eq. 1 can be re-written as

$$P = P_0 + \eta \frac{kT}{e} \frac{L}{S} \left[\frac{1}{M} \sum_{m=0}^{M-1} \phi(m) \right] . \quad (4)$$

ELECTRON CLOUDS DURING BEAM INJECTION

To illustrate the relevant features of an electron cloud build up as a function of the bunch passage m, a typical evolution of the bunch-to-bunch electron flux to the wall during one turn is shown in Fig. 1. The blue circles correspond to a simulation result using CSEC [2] for a bunch train of 60 bunches spaced by 107 ns and 10^{11} protons/bunch. With this bunch spacing, a RHIC revolution corresponds to the passage of M=120 bunches.

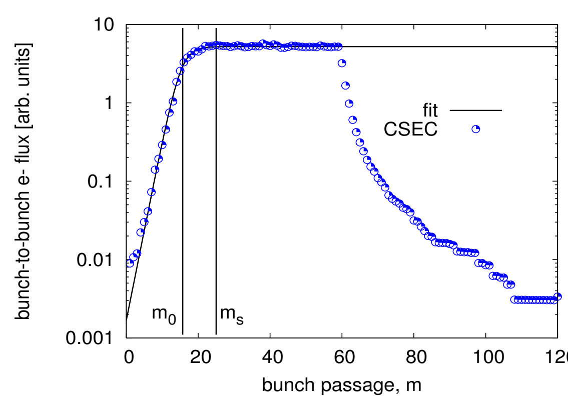

Figure 1: Average bunch-to-bunch electron flux evolution during a RHIC revolution. A saturation level is reached after about 25 bunches.

The observed initial exponential growth going to a saturated value is well fitted (black line in Fig. 1) using [2]

$$\phi(m) = \phi_s \frac{e^{(m-m_0)/B}}{1 + e^{(m-m_0)/B}} , \quad (5)$$

where ϕ_s represents the saturated electron flux, m_0 is the bunch corresponding to a flux $\phi_s/2$, and B controls the rise time. These parameters depend on the beam and wall surface parameters.

Combining Eqs. 4 and 5, the pressure as the beam bunches are being injected is:

$$P(m) = P_0 + A_P \ln\left[1 + e^{(m-m_0)/B}\right] \tag{6}$$

where the constant A_P has been introduced:

$$A_P = \eta \frac{LkT}{eS} \frac{\phi_s}{MB} \; . \tag{7}$$

Assuming $m_0/B \gg 1$ (as it is seen *a posteriori* in Table 1), both the electron flux and the pressure show two different regimes:

1. For $m \ll m_0$, the factor $e^{(m-m_0)/B} \ll 1$, and the electron flux is

$$\phi(m) = \phi_s \frac{e^{(m-m_0)/B}}{1 + e^{(m-m_0)/B}} \approx \phi_s e^{(m-m_0)/B} \; , \tag{8}$$

   while the pressure becomes

$$\begin{aligned} P(m) &= P_0 + A_P \ln(1 + e^{(m-m_0)/B}) \approx \\ &\approx P_0 + A_P e^{(m-m_0)/B} \; . \end{aligned} \tag{9}$$

   Both the electron flux and the pressure exhibit an exponential growth.

2. For $m \gg m_0$, the factor $e^{(m-m_0)/B} \gg 1$, and the flux is

$$\phi(m) = \phi_s \frac{e^{(m-m_0)/B}}{1 + e^{(m-m_0)/B}} \approx \phi_s \; , \tag{10}$$

   while the pressure becomes

$$\begin{aligned} P(m) &= P_0 + A_P \ln(1 + e^{(m-m_0)/B}) \approx \\ &\approx P_0 + A_P (m - m_0)/B \; . \end{aligned} \tag{11}$$

   The pressure $P(m)$ is linearly dependent on the bunch passage number m.

Consistent with these two regimes, the flux in Fig. 1 first shows exponential growth (for $0 < m < m_0$), followed by a constant regime after saturation (for $m \gg m_0$).

Figure 2 shows the injection of 110 bunches spaced by 107 ns with an average bunch intensity of 8×10^{10} protons. The top plot in Fig. 2 shows the time evolution for both pressure (red line), and the electron signal averaged over one turn (black dots). The injection is temporarily halted for about two minutes after 45 bunches (12h12m). Injection resumed (12h14m) and finally finished at 12h20m. The electron flux $\phi = dI/dl$ is directly proportional to the voltage in the electron detector, ED (see Eq. 12).

Figure 3 shows the evolution of the pressure as a function of the total beam intensity at two different locations: in the baked stainless steel region BO10 (red points), and in the BO2 section (blue dots), the latter corresponding to the same data, as shown in Fig. 2. The black line in both cases corresponds to a fit to the experimental data following Eq. 6. No EDs are installed in BO10, but the good agreement of the fit to the BO10 experimental data supports the notion of electron clouds as the cause of the pressure rise. The two different regimes corresponding to Eqs. 9 and 11 are noticeable for both BO2 and BO10 (first exponential growth, and second linear regime).

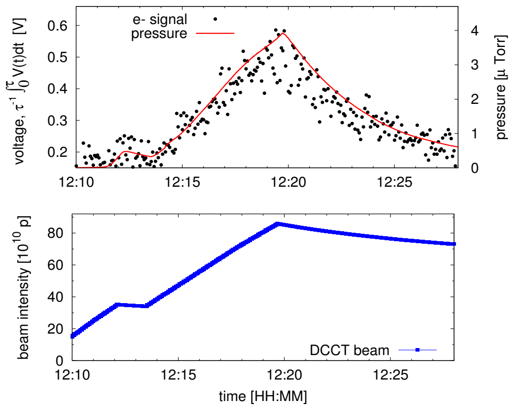

Figure 2: Dynamic pressure and electron signal evolution (top plot), as the blue beam is injected (bottom plot).

Table 1: Fit results for Fig. 3.

parameter	unit	**BO2**	**BO10**
m_0	...	37	72
B	...	2.0	2.1
A_P	Torr	3×10^{-7}	9×10^{-9}
P_0	Torr	3.6×10^{-9}	2.5×10^{-10}

The fit results are shown in Table 1. Fewer bunches are required to trigger electron clouds in unbaked surfaces ($m_0 = 37$ vs 72), and that pressure rises are around two orders of magnitude lower ($A_P = 3\times10^{-7}/9\times10^{-9} \approx 30$). According to Eqs. 6 and 7, this can be due to lower electron fluxes ϕ_s, lower electron desorption coefficients η, or both.

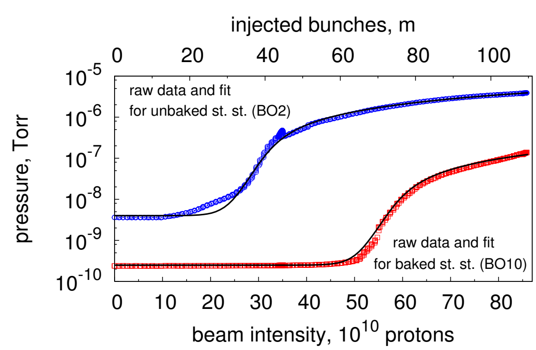

Figure 3: Pressure evolution as a function of the beam intensity (bottom horizontal axis) and/or number of injected bunches (top axis) at two different RHIC regions, BO2 (unbaked) and BO10 (baked). The black line is a fit using Eq. 6.

CALCULATION OF ELECTRON-IMPACT DESORPTION COEFFICIENT

The presence of the electron detector at BO2 allows to infer the desorption coefficient, η after calibration of the ED [2]. Using the beam pipe radius, $R_p = 6$cm, the electron flux is rewritten in terms of the ED voltage V by [1, 2]

$$\frac{dI}{dl} = \frac{2\pi R_p}{ZGA_{\mathrm{ED}}T_{\mathrm{eff}}}\, V\,, \tag{12}$$

where $A_{\mathrm{ED}} = 78\mathrm{cm}^2$ is the area of the electron detector, $Z = 50\Omega$ is the line impedance, $G = 1600$ is the amplifier gain, and T_{eff} is the effective transparency of the electron detector. T_{eff} depends on the electron energy, and a good average value is 5% [2, 3]. Since the BO2 beam pipe is made of the same material and no external electromagnetic fields are present [1], we assume that the electron flux is the same throughout the entire region. The (CO) pumping speed is $2S = 140$ l/s and the distance between pumps is $2L = 17$ m. Using Eqs. 1 and 12, we can express the pressure as a function of the electron detector voltage by

$$P = P_0 + \eta\frac{kT}{e}\frac{L}{S}\frac{2\pi R_p}{ZGA_{\mathrm{ED}}T_{\mathrm{eff}}}\langle V\rangle_\tau\,, \tag{13}$$

where, $\langle V\rangle_\tau$ is the electron detector voltage time averaged over one turn (as in Eq. 3).

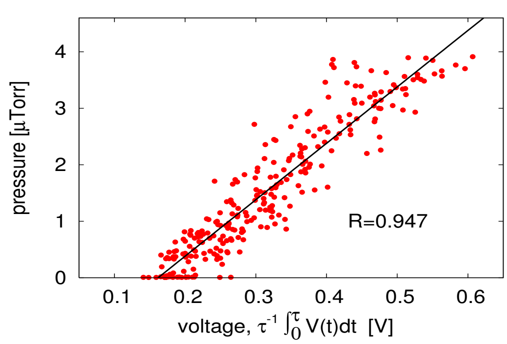

Figure 4: Linear relation between pressure and electron signal in Fig. 2.

Pressure P and electron signal $\langle V\rangle_\tau$ shown in Fig. 2 are plotted in Fig. 4. The linear relation expressed in Eq. 13 is confirmed. This linear relation has been found also in other accelerators [5]. The black line shows the result of a linear regression applied to the red points, which allows to calculate η. For the case in Fig. 2, the correlation coefficient is R=0.947, the error in B is 2%, and the desorption coefficient (CO equivalent) is $\eta = 0.05 \pm 50\%$ molecules/electron. The error in η stems from the uncertainty in the pressure readings and pumping speed [4]. Although results are given as CO equivalent, we note that the dominant rest gas is H_2.

This analysis is performed for all the fills during 2003 that produced electron detector signals above the noise level. Figure 5 shows the evolution of the calculated desorption coefficient until the end of the run. As expected, this coefficient decreases with time due to the bombardment dose. In about 6 weeks, η decreased by almost a factor of 5. An estimate of the total bombardment dose is difficult because of the large ED signal-to-noise ratio. A measurement of the energy spectrum and its comparison with simulation results is performed in Refs. [1, 2], where a linear relation between electron flux and pressure is shown for a baked stainless steel surface.

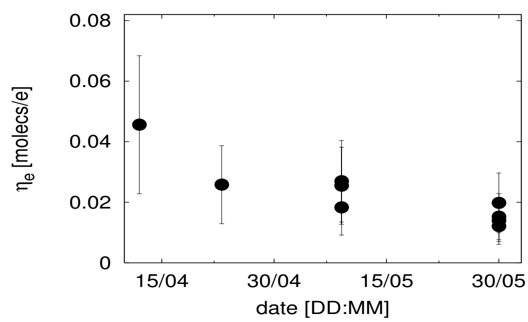

Figure 5: Summary of all calculated desorption coefficients for the unbaked surface BO2.

SUMMARY

Analytical formulae are found that describe the pressure rise in the presence of an electron cloud as the beam bunches are injected into the RHIC ring. This pattern is characterized by an initial exponential growth that continues until about the time that the bunch at which cloud saturation occurs is injected, then the growth enters a linear regime. A linear relation between the pressure and the electron flux into the wall due to an electron cloud is shown. The electron desorption coefficient η is inferred from the analysis of the experimental data. For unbaked stainless steel and assuming CO as the only desorbed gas, this value is about 0.05 at the beginning of the run, and decreases to 0.01 after 6 weeks of machine operation due to scrubbing.

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