# ELECTRON CLOUDS AND VACUUM PRESSURE RISE IN RHIC*

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*Abstract*

The luminosity in RHIC is limited by vacuum pressure rises, observed with high intensity beams of all species ($Au^{79+}$, $d^+$, $p^+$). At injection, the pressure rise could be linked to the existence of electron clouds. In addition, pressure rises in the experimental regions may be caused by electron clouds. We review the existing observations, comparisons with simulations, as well as corrective measures taken and planned.

## 1 INTRODUCTION

Since 2001 vacuum pressure rises were observed in RHIC with intense ion beams [1–7]. While this could be seen initially only at injection, later observations were also made at store and at transition [4]. Pressure rises were observed with all species ($Au^{79+}$, $d^+$, $p^+$), and until recently, only in the warm interaction regions. In Tab. 1 the main machine parameters are given for the different species. A full parameter list can be found in Ref. [8].

Table 1: Selected machine and beam parameters for various species in RHIC.

| parameter | $Au^{79+}$ | $d^+$ | $p^+$ |
|---|---|---|---|
| atomic number $Z$ | 79 | 1 | 1 |
| mass number $A$ | 197 | 2 | 1 |
| revolution time $T_{rev}$ | | 12.8 $\mu$s | |
| harmonic no. $h$, acceleration | | 360 | |
| harmonic no. $h$, storage | 2520 | | 360 |
| full bunch length, injection | 20 ns | 15 ns | 15 ns |
| full bunch length, storage | 5 ns | 5 ns | 10 ns |
| no. of bunches | | up to 111 | |
| bunch spacing | | multiples of 108 ns | |
| ions per bunch $N_b$ | $10^9$ | $10^{11}$ | $2 \cdot 10^{11}$ |

A number of effects were considered to account for the observed pressure rises [3]. The existence of electron clouds in conjunction with pressure rises could be confirmed by observing the tune shift in bunch trains [3], and by direct observation with electron detectors [4]. The ionization of rest gas by the beam, subsequent acceleration of the ions in the field of the beam, and the desorption when the ions hit the wall, is an effect that is too small to explain the pressure rise observations. The contributions of beam loss induced desorption are still under investigation.

In Tab. 2 the pressure rise observations are summarized. Pressure rises of more than a decade were observed at injection, transition, and during stores.

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At injection, electron clouds could be observed with electron cloud detectors. At transition, pressure rises were observed with both $Au^{79+}$ and $d^+$, although direct electron observations were only made in one case with large beam loss. The pressure rise at transition does not appear to be sensitive to the bunch spacing, and may therefore not predominantly driven by electron clouds [9]. Protons do not cross transition.

At store pressure rises of more than a decade are observed after bunches are transferred from the accelerating rf system with harmonic number 360, into the storage rf system with harmonic number 2520. In this process the bunch length is reduced to about half.

Table 2: Overview of pressure rise and electron cloud observations in RHIC, to date. Only pressure rises of more than a decade are considered. Electron cloud observation refers to observation with electron detectors. Protons do not cross transition in RHIC.

| | $Au^{79+}$ | $d^+$ | $p^+$ |
|---|---|---|---|
| pressure rise locations | warm | | warm/cold |
| **injection** | | | |
| pressure rise observed | yes | yes | yes |
| e-clouds observed | yes | yes | yes |
| **transition** | | | |
| pressure rise observed | yes | yes | N/A |
| e-clouds observed | yes (with large loss) | no | N/A |
| **store** | | | |
| pressure rise observed | yes | no | yes |
| e-clouds observed | no | no | no |

## 2 ELECTRON CLOUD OBSERVATIONS

Electron clouds were observed in three ways. First, through their effect on the vacuum pressure. Second, through their effect on the coherent tune along a bunch train [3]. Third, through dedicated electron detectors [10].

Fig. 1 shows in the upper part the electron cloud density as a function of time, along with the bunch intensity of the bunches in the train. For this case 110 proton bunches were injected, with 108 ns spacing, and a total intensity of $88 \cdot 10^{11}$. In the lower part of Fig. 1 an electron cloud simulation is shown with the same beam parameters, and variations in the secondary emission yield (SEY) from 1.7 to 2.1. With an SEY of about 1.9 the experimental observations can be matched, including the effect of bunches of lower intensities in the beginning of the bunch train [5]. For the simulations the code CSEC [3] by M. Blaskiewicz was used.

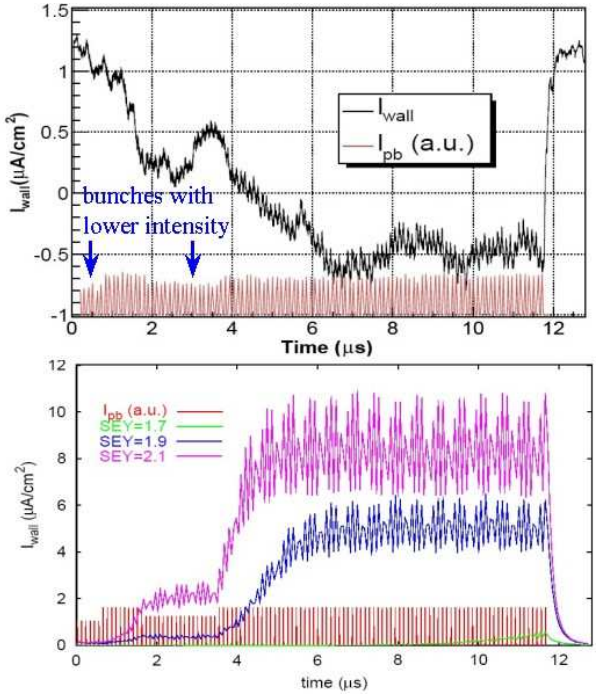


Figure 1: Upper part: Electron cloud observation in RHIC with an electron detector. Note that the cloud density follows the bunch intensity. Lower part: Corresponding electron cloud simulation [5].

Fig. 2 shows another proton fill with 108 ns spacing. After a certain number of bunches are filled, an electron signal begins to appear in one of the detectors. It rises rapidly with the bunch number, slightly decays when the fill is interrupted, and saturates as the fill continues. The electron signal, on a linear scale, is well correlated with a pressure measurement, on a logarithmic scale. The fact that the pressure is nonlinearly dependent on the electron cloud density indicates that the pressure is not simply the result of electron desorption of electrons in the cloud.

## 3 RECENT PRESSURE RISE OBSERVATIONS

We summarize here pressure rise observations in the 2003/2004 operating period. Previous observations can be found elsewhere [1–7]. In gold-gold operations pressure rises in both rings, and one of the experiments were the most limiting luminosity limitations.

### *3.1 A vacuum instability in the Blue ring*

The Blue beam intensity was limited by pressure rises in the collimator region. The collimators were not baked due to scheduling conflicts during the last shut-down. The Yellow collimators were baked, and no vacuum instabilities were observed there.

Fig. 3 shows an example of a pressure rise instability. In the upper part the total beam intensity of gold beams in

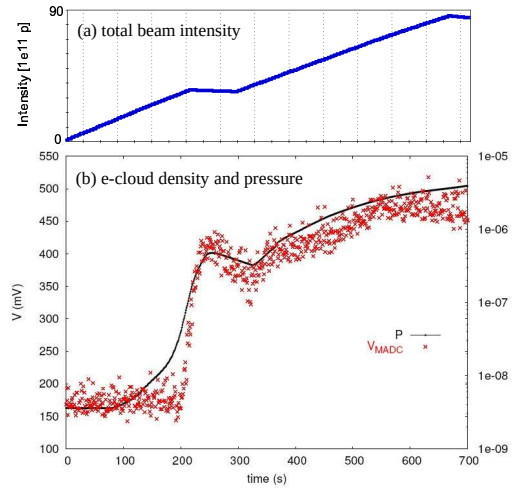


Figure 2: In part (a) total beam intensity during proton filling, bunches are spaced by 108ns. Part (b) shows an electron detector signal (red crosses, left scale in mV), and the pressure (black line, right scale in Torr).

both rings is show as a function of time. 56 bunches are injected in the Blue ring first, and a slight pressure increase can be observed. The Yellow beam is filled second, and both beams are accelerated. A pressure increase is visible when transition is crossed, as the bunches get shorter. The pressure drops back after the transition crossing. When the bunches reach the flattop energy, they are transferred from the accelerating rf system with harmonic number 360 into the storage rf system with harmonic number 2520. In the process, the bunch length is reduced to about 50%. After rebucketing, the pressure increases exponential with a time constant of about 10 seconds until the vacuum interlock system aborts the beams.

In a test, Au bunches with different spacing were injected. Injection of 53 bunches with 3 buckets spacing

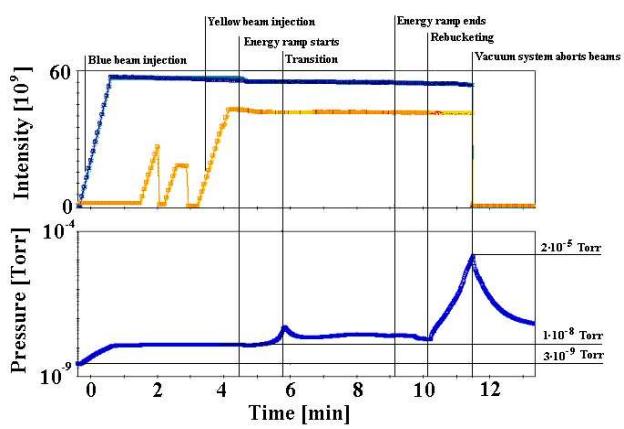


Figure 3: A vacuum instability in the Blue ring. The upper part shows the total gold intensity of 56 bunches for both rings during injection, acceleration, and storage. The lower part shows the pressure in the collimator region, with an exponential increase after rebucketing.

(108 ns), and close to $10^9$ Au ions per bunch lead to a pressure of $7 \cdot 10^{-6}$ Torr. Injection of approximately the same amount of beam with 6 buckets spacing lead to a pressure of only $4 \cdot 10^{-8}$ Torr. In another test, one of the Blue collimators was moved to create a local beam loss of $7 \cdot 10^7$ Au ions within 5 second. This did not induce any pressure rise.

The observed pressure rise is sensitive to bunch length and bunch spacing, but not to local beam losses. This is consistent with electron clouds as the mechanism driving the pressure rise. No electron detectors are installed in the collimator region.

### 3.2 *Pressure rise in an interaction region*

In one of the experiments, PHOBOS, pressure rises of about a decade were frequently observed after rebucketing [12]. The elevated pressure lasted for minutes to two hours, and dropped back spontaneously. The increased pressure rise created intolerable background for the experiment. Fewer bunches did temporarily suppress the effect.

Trains of 61, 56, and 45 bunches were injected and ramped during Au-Au operation in 2003/2004. At storage energy, the bunches are transferred from the accelerating rf system, with 36 ns bucket length, to the storage rf system, with 5 ns bucket length. The bunch rotation process used for rebucketing halves the bunch length and doubles the peak intensity. After the rebucketing, the pressure in PHOBOS could rise by about a decade (see Fig. 4).

Some peculiar features point to electron clouds as the most probable cause of this pressure rise. First, the bunch length dependence of the effect. Second, the persistence over time. After a random time interval (spanning minutes to 2 hours) some threshold is crossed and the effect is switched off. Third, the surface properties in the experimental region. For the experiment a 12 m long beryllium pipe with 3.6 cm radius is installed. Beryllium has a SEY of up to 2.8. Fourth, the independence from the beam energy. The effect could be observed with gold beams of 100 GeV/u and 31.2 GeV/u.

The pressure rise did only occur in some of the stores. No narrow parameter ranges could be found that would predict the occurrence of the pressure rise after rebucketing, nor the time after which the pressure would drop again spontaneously (Fig. 5). The pressure drop can be seen as a first order phase transition [11].

In simulations it was found that a SEY of 2.5 leads to no electron clouds before, and electron clouds after rebucketing [12]. An important finding of the simulation is that the electron cloud effect is concentrated at the ends of the beryllium pipe.

### 3.3 *Pressure rise in cold regions*

A pressure rise in the cold regions was first observed in 2004 (Fig. 6). In a test, 111 bunches with, on average, $1.4 \cdot 10^{11}$ protons, were injected in one of the rings. In some areas up to 3 decades pressure rise were observed in

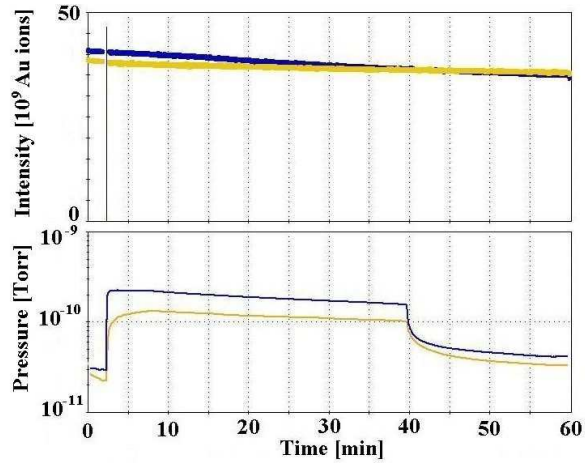


Figure 4: Pressure in store at the PHOBOS experiment. In the upper part the total Au intensity of both beams is shown. The vertical line denotes the time of rebucketing. After rebucketing the pressure rises by about a decade (lower part), and drops back spontaneously after less than 40 min.

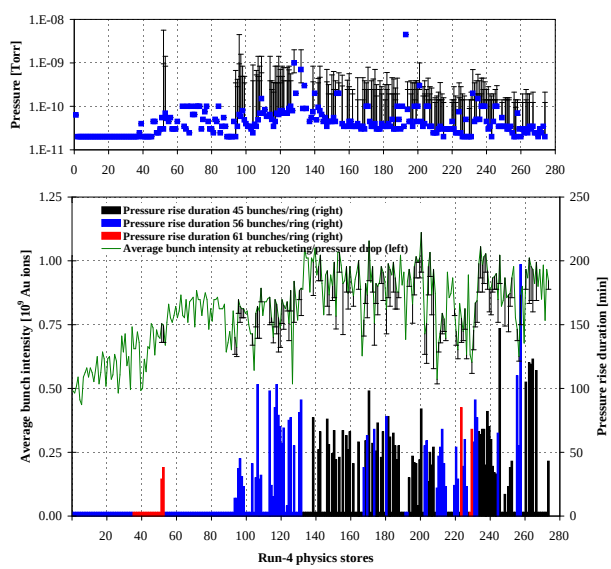


Figure 5: History of the PHOBOS pressure rise during the RHIC Run-4. In the upper part, the pressure in IR10 is shown at rebucketing for the physics stores of Run-4. For stores with a pressure rise after rebucketing, also shown are the maximum pressure and the pressure when it begins to drop sharply. In the lower part on the left scale the bunch intensity, averaged over all bunches in the Blue and Yellow rings, is depicted. Stores with a PHOBOS vacuum problem also show the average bunch intensity at the time when the pressure begins to drop sharply. In the lower part on the right scale, the duration of the pressure problem is shown, ordered into stores with 45, 56, and 61 bunches per ring. Note that the last 14 stores are with beams at 31.2GeV/u, all other stores are with beams of 100.0GeV/u.

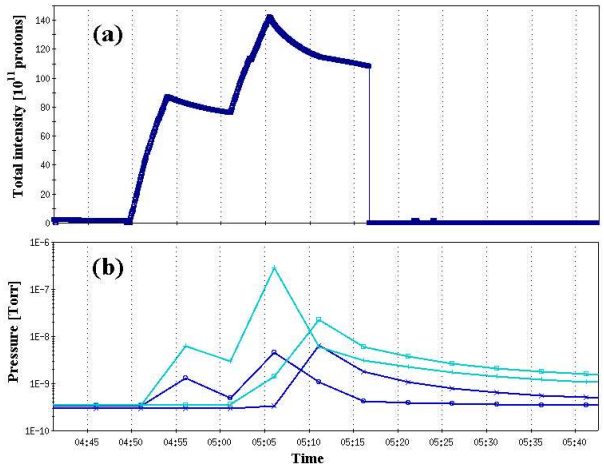


Figure 6: Pressure rise in a Blue cold arc. In the upper part the total proton intensity of a fill is shown. 111 bunches with an average bunch intensity of $1.4 \cdot 10^{11}$ are injected. The lower part shows the pressures reading of a cold cathode gauge. Note the gauges are connected by a low conductance conduit and the pressure rise in the cold volume is up to three orders of magnitude higher.

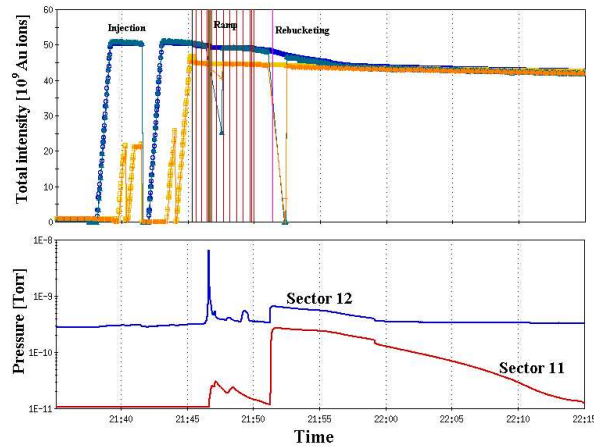


Figure 7: Total intensities of gold beams during injection, acceleration and storage in the upper part. The pressure rise in store is caused by shortening the bunches. Pressure readings in the sector 11 and sector 12. Both gauges are 7.6 m from the IP. Between the sector 11 gauge and the IP is a 4 m long NEG coated beam pipe.

the gauges. The beam lifetime is visibly affected by the increased pressure, in the warm and cold sections. Note that the gauges are connected to the cold vacuum through 1.5 m long conduits with approximately 1 l/s conductance. Thus the pressure rise in the beam pipe can be up to 3 orders of magnitude larger. No increased heat load was observed in the test. A minimum of 150 W additional heat load over a sufficiently long period is needed for detection.

## 4 COUNTER MEASURES

A number of counter measures are considered to suppress the pressure rises in RHIC. The most basic of these is the bake-out of all bakeable element in the warm regions. However, occasionally this is prevented by scheduling conflicts in shut-downs, after new devices are installed, or the vacuum was let up to air for other reasons. Other counter measures, discussed below, include coated beam pipes, optimized bunch patterns, solenoids, and scrubbing.

### *4.1 Coated beam pipes*

For test purposes, 60 m of NEG coated beam pipes were installed in the warm regions of RHIC [13]. From CERN measurements we expected a SEY of 1.4 after activation, and 1.7 after saturation. The NEG pipes were activated at 250C for 2 hours, and should provide a pumping speed of 300 l/m/s.

Fig. 7 shows the readings of 2 gauges in an interaction region, both 7.6 m from the interaction point. Between the gauge in sector 11 and the interaction point is a 4 m long NEG coated beam pipe. This gauge shows a lower base pressure and does not rise to the same pressure that is observed in the gauge on the other side of the interaction point, without a NEG coated pipe.

Although the installed beam pipes with NEG coating are only of limited length, the observations indicated that they are effective in reducing the pressure rise in RHIC. It is planned to replace almost all warm beam pipes with NEG coated ones.

### *4.2 Bunch patterns*

Due to limitations in the injection kicker rise time, bunches in RHIC have a minimum spacing of 3 buckets, but can be distributed almost arbitrarily otherwise. Given a fixed number of bunches we were looking for the bunch pattern that minimizes the average and peak electron cloud density [14]. The two most extreme bunch pattern are one in which a long train with minimum bunch spacing is followed by a long gap, and one in which the bunches are distributed as uniformly as possible.

Different bunch patterns were studied in simulations and experiments [14]. In simulations 68 bunches were distributed in a number of different pattern. In Figs. 10 and 9 are the two most extreme cases displayed: a long bunch train with minimum bunch spacing followed by a long gap, and a close to uniform distribution. In the simulations, the maximum and average electron cloud density is minimized with the most uniform bunch distribution along the circumference. This is supported by experimental observation in Run-3 (Fig. 8) and Run-4, and is also consistent with the operational experience at the B-factories [15–18].

### *4.3 Solenoids*

Also for test purposes, about 60 m of solenoids are installed in RHIC, with a maximum field of 7 mT. Fig. 11

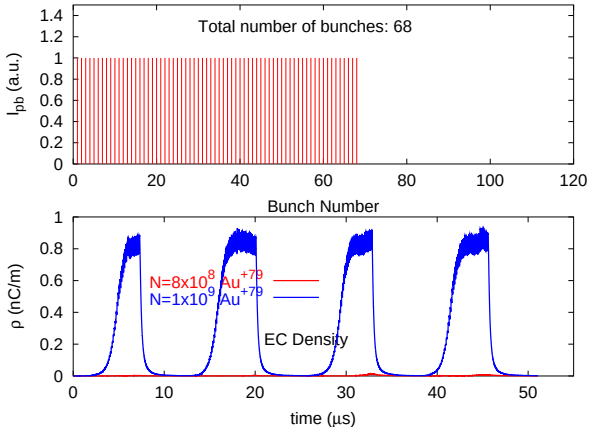


Figure 8: Electron cloud simulation for 68 bunches, in a long train with 3 buckets spacing, followed by a long gap. In the upper part the filled bunches are indicated as lines above one of the 120 potential buckets that can be filled with 3 buckets bunch spacing. The lower part shows the electron cloud evolution over 4 turns for two different bunch intensities.

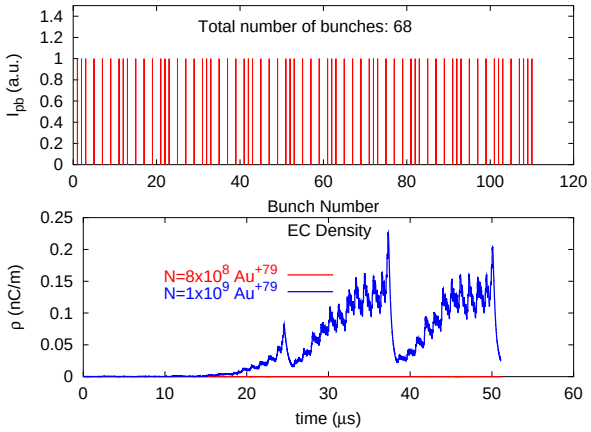


Figure 9: Electron cloud simulation for 68 bunches, in a close to uniform distribution along the circumference. In the upper part the filled bunches are indicated, lower part shows the electron cloud evolution over 4 turns for two different bunch intensities.

shows that the solenoidal field is effective in reducing the observed electron cloud density by a factor 4. In another test, the pressure rise could be reduced by a factor 4 with solenoid fields of only 0.5 mT. In some rare instances, pressure increases were observed with solenoids [4]. For the near future, it is not planned to install solenoids on a large scale. The cost of installing solenoids is comparable to the cost of NEG coating the beam pipes. While solenoids are only effective in suppressing electron clouds, NEG coating suppresses all pressure rises. In addition, solenoids could be wound on top of the NEG coated pipes later, if necessary.

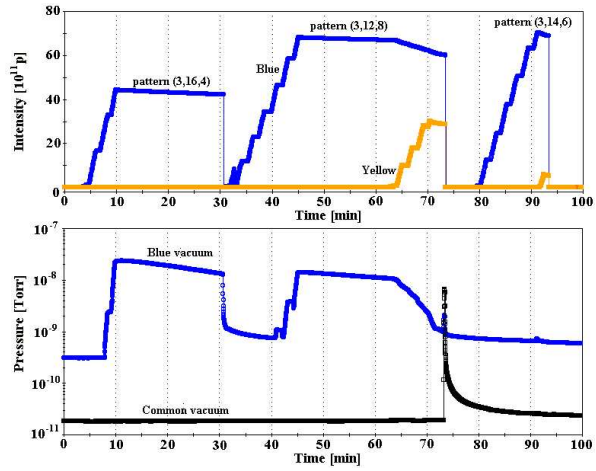


Figure 10: Beam test of different bunch patterns. In all three cases, bunches in the trains had 3 buckets spacing. In the first case trains of 16 bunches with gaps of 4 missing bunches were injected. In the second case, trains of 12 bunches with gaps of 8 missing bunches were injected. In the third case, trains of 14 bunches with gaps of 6 missing bunches were injected [14].

## 4.4 *Scrubbing*

With repeated high intensity fills, it can be observed that more and more beam can be injected for the same pressure rise [19]. One such example is shown in Fig. 12, where in the second fill 10% more beam is injected for the same pressure rise. Generally scrubbing is more effective in locations with high pressure. An effect could only be seen consistently in locations with more than $10^{-7}$ Torr. With scrubbing the pressure rise bottle necks can be removed successively. However, scrubbing may need a substantial amount of time. During the scrubbing tests, some of the electronic modules for the beam position monitors in the ring were damages. These are moved out of the tunnel into the adjacent alcoves.

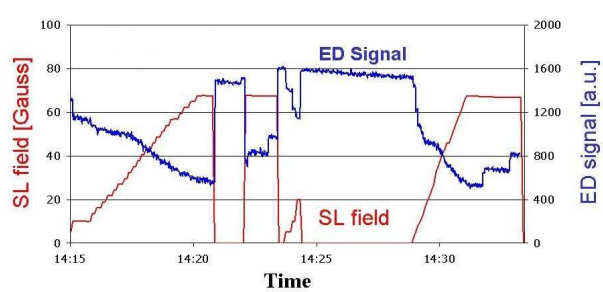


Figure 11: Effect of solenoid field on the electron cloud density. The electron signal (blue, right scale in arbitrary units) is clearly anti-correlated with the solenoid field (red, left scale in Gauss).

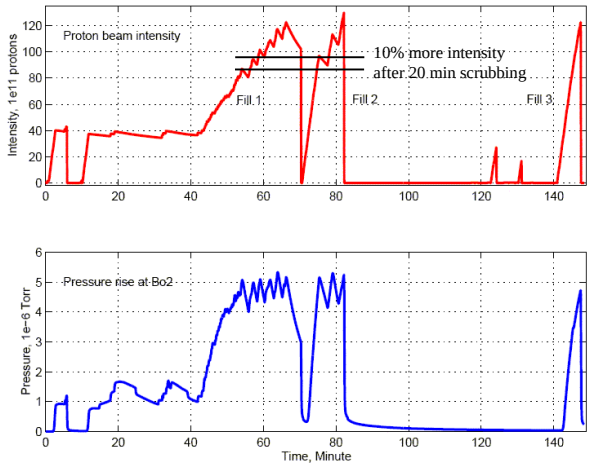


Figure 12: Observation of scrubbing effect. In the upper part the total beam intensity of a proton fill is shown, in the lower part the pressure in a warm location in the Blue ring. With the second fill 10% more beam can be injected for the same pressure rise [19].

## 5 SUMMARY

Intense ion beams in RHIC can form electron clouds that cause an increase in the vacuum pressure rise. So far no other electron cloud driven effects were observed that are detrimental to the machine operation. Pressure rises were seen with all species ($Au^{79+}$, $d^{+}$, $p^{+}$), in both warm and cold regions. At injection, electron clouds limit the beam intensity that can be filled in the two rings. At store, electrons clouds can create unacceptable experimental background thus limiting the luminosity.

To suppress the electron cloud driven pressure rises a number of counter measures are used. All bakeable elements are baked before a run starts. NEG coated beam pipes were successfully tested, and it is planned to installed them on a large scale. Bunch patterns are used that minimize the electron cloud density. Solenoids were successfully tested, but will not be used on a large scale near term. Scrubbing appears possible after all electronics is removed from the tunnel.

## 6 ACKNOWLEDGMENTS

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