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1 Abstract

With large scale installation of NEG coated pipes at RHIC, higher intensity beams were allowed in FY2005 polarized proton run. In this tech note, the performance of NEG coating with respect to electron cloud induced pressure rise is presented. Issues related to NEG coating and the associated effects on beams are discussed.

2 Summary

RHIC polarized proton beam intensity in FY2005 has increased to 10^{11} protons per bunch with total 111 bunches (bunch spacing of 108 ns), from FY2004's 0.7×10^{11} protons per bunch with total 56 bunches (bunch spacing of 216 ns). Among others, the improvement of beam induced pressure rise has been benefited from the large scale installation of NEG coated beam pipes. Total 200 meters of NEG coated pipes were installed in FY2005, in addition to 50 meters installed in FY2004 for beam test. The locations with highest dynamic pressure rise in both rings were at least partially equipped with NEG pipes. Elimination of these 'hot' spots in FY2005 run has allowed higher intensity beams.

The pressure rise pattern at the straight sections equipped largely by NEG pipes has shown significant difference compared with those without NEG pipes. The pressure rise without NEG pipes was usually the highest in the middle of long straight sections. Now, with NEG pipes the middle of the straight section has lower pressure rise than at the ends of sections (where the pressure rise is also reduced).

The saturated NEG pipes have been investigated with beam. Effects and pattern of pressure rise reduction similar to the un-saturated NEG have been observed.

Electron cloud could affect the beam parameters, such as the coherent tune shift, incoherent tune spread, or even causing beam instability and emittance blow-up. It is not very clear at the moment what these effects are at the RHIC operation under upgrade conditions. On the other hand, large scale installation of NEG pipes raises the threshold of electron multipacting through the reduction of secondary electron yield (SEY), and improves pressure rise through the reductions of both SEY and electron stimulated desorption. The harmful effect of electron cloud and pressure rise could be prevented in first place by significant reduction/elimination of the electron cloud.

During two years' period, none of possible complications of NEG coating discussed in [1] has caused serious concerns, such as the in-sufficent activation, frequent need of re-activation, damage of the coating, etc. Nevertheless, with more installations, longer time durations, and unavoidable machine maintenance and modifications, the issues such as the activation, re-activation, coating's lifetime, etc. will require more attentions. The Tandem NEG test stand could provide useful assist on many aspects of this requirement, such as to optimize the activation and re-activation in terms of teperature and time period, etc. [2].

3 Performance of NEG coatings

For FY2005, there were total 250 meters of NEG pipes installed in RHIC, which has effectively eliminated the worst pressure rise locations in both rings, and hence allowed proton beams with higher intensities.

This can be shown in Fig.1 and Fig.2 for pressure rises for similar Blue and Yellow beam intensities in RHIC, in 2004 and 2005, respectively. Since most NEG pipes (200 m) were installed in 2005, the comparison of pressure rise with respect to 2004 should be sufficient for the illustration.

The pressure rise for Blue ring is shown in Fig.1. Both beam injections are with the 111-bunch injection pattern, which implies the bunch spacing of 108 ns. The bunch intensities are the same, 2×10^{11} protons. The case in

2004 is Fill 5350, and the case in 2005 is Fill 7333. Note that 7333 was with less beam loss during the filling, which may cause stronger electron cloud and higher pressure rise.

The pressure rises at all 12 single Blue beam Q3 to Q4 straight sections are shown. For each section, the vacuum gauge reading of pw3.2 is shown. This gauge is located at the middle of the 34 meters long straight section. Without NEG pipes, the pw3.2 pressure rise is usually about an order of magnitude higher than pw3.1 and pw3.3, which are located at the each end of straight sections.

The pressure rises shown in Fig.1 are the electron cloud induced ones. Along with the bunch injection, at the threshold of electron multipacting, pressure starts to rise, which is due to the electron stimulated gas desorption with the electrons hitting the chamber wall.

It can be noticed that the pressure rises at two worst locations in 2004, namely Bi8 and Bo2, were reduced by more than an order of magnitude in 2005 (Bi8 was baked in 2005 but not in 2004, therefore, the reduction in pressure rise is not completely attributed to NEG pipes.) Also, 4 locations with 19 meters or more NEG pipes in 2005 did not show any pressure rise. Among them, Bi5, Bo7, and Bo11 remain at 10^{-11} Torr, and Bi9 at about 10^{-10} Torr, which is the static pressure.

A detailed break-down of the peak pressure rise and the NEG installation in 2004 and 2005 is shown in Table 1.

Location	Peak Pressure	Peak Pressure	NEG Pipes	NEG Pipes
	2004	2005	2004	2005
Bi1	6.6	3.2	0	0
Bo2	200	8.6	5	11
Bo3	2.8	5.7	0	0
Bi4	7	4.7	0	0
Bi5	0.4	0.001	0	19
Bo6	2.8	4.2	0	0
Bo7	0.8	0.001	0	19
Bi8	200	4.2	0	12
Bi9	0.8	0.01	10	31
Bo10	16	4	0	3
Bo11	7	0.001	0	31
Bi12	12	4.1	0	0
	10^{-8} Torr	10^{-8} Torr	Meters	Meters

Table 1: Peak pressure rise at pw3.2 of all 12 Blue Q3-Q4 straight sections of Fill 5350, 2004 and Fill 7333, 2005, and the NEG pipe installations.

A review of these data shows:

- All locations with newly installed NEG pipes had lower pressure rise in 2005 than that in 2004. All 4 locations with 19 meters or longer NEG pipes had no pressure rise, which implies that electron cloud might have been eliminated there.
- All other locations without NEG pipes have similar pressure rise in 2004 and 2005, indicating that the pressure rise improvements showing above are indeed due to the NEG coatings.

In Fig.2, a counterpart of the Yellow beam induced pressure rise is shown. Again, both cases are with the 111-bunch injection pattern. The bunch intensities are also the same, 1.5×10^{11} protons. The case in 2004 is Fill 5350, and the case in 2005 is Fill 7329.

A detailed break-down of the peak pressure rise and the NEG installation is shown in Table 2.

Location	Peak Pressure	Peak Pressure	NEG Pipes	NEG Pipes
	2004	2005	2004	2005
Yo1	200	13	5	15
Yi2	1.8	0.3	10	22
Yi3	0.2	0.3	0	0
Yo4	8.2	14.8	0	7
Yo5	5.9	0.1	0	0
Yi6	1.2	2.7	0	17
Yi7	38	24	0	0
Yo8	0.1	0.002	0	19
Yo9	2	3	0	0
Yi10	0.4	0.001	21	31
Yi11	0.6	0.7	0	0
Yo12	14	29	0	0
	10^{-8} Torr	10^{-8} Torr	Meters	Meters

Table 2: Peak pressure rise at pw3.2 of all 12 Yellow Q3-Q4 straight sections of Fill 5350, 2004 and Fill 7329, 2005, and the NEG pipe installations.

A review and comments are as follows:

- Most locations with NEG coated pipes had lower pressure rise in 2005 than in 2004. The two locations, which have some NEG pipes installed but pressure rise is a little higher in 2005, are as follows,
  - At Yo4, the installed 7 meters of NEG pipes are close to pw3.3. Also at the time, an ion pump close to pw3.2 was turned off, which was on in 2004. In addition, a newly installed stochastic cooling kicker may have caused some pressure rise.
  - At Yi6, a secondary vertical collimator was installed in 2005 between pw3.1 and pw3.2.
- Most locations without NEG pipes show comparable pressure rise in 2004 and 2005. One exception is,
  - Yo5. The pressure rise reduction there might be due to the anti-grazing ridges, which will be reported elsewhere.

In a brief summary, we have shown that the newly installed 200 meters of NEG pipes have effectively reduced the beam induced pressure rise in both rings, especially at the worst locations.

In the beam study of June 24, 2005, with very limited beam scrubbing, total 111 bunches with 3×10^{11} protons per bunch were injected into Blue ring, ended up with total 3.3×10^{13} protons, then a similar beam was injected into Yellow ring, ended up with 2.6×10^{13} protons in Yellow. The RF voltage was then switched from 100 kV to 300 kV, which has shortened the bunch length, causing stronger electron multipacting and higher pressure rise (usually in an energy ramp, the end of the RF voltage switching gives rise to highest dynamic pressure rise of entire ramp). During this period, the highest pressure rise in the entire ring was no more than 10^{-6} Torr, which was tolerable from vacuum point of view. The NEG installations have clearly contributed to this improvement.

4 Characteristics of pressure rise at NEG coated pipes

Without NEG pipes, the electron cloud induced pressure rise at the Q3-Q4 straight sections is normally the highest at pw3.2, and about an order of magnitude lower at both pw3.1 and pw3.3. With similar pumping capacity of ion pumps close to each vacuum gauge, the ones at pw3.1 and pw3.3 are assisted by cryogenic pumping from cold bore. In addition, the electron multipacting at the middle of straight sections is suspected to be stronger.

For the straight sections equipped mostly with NEG pipes, the pressure rises at pw3.1, pw3.2, and pw3.3 are all reduced. However, the one at pw3.2 becomes the lowest, compared with pw3.1 and pw3.3.

Moreover, there is a difference in the pattern of pressure rise between pw3.1, at the end of straight sections close to interaction regions, and pw3.3, at the other end of straight section. For all 7 straight sections fully or largely NEG covered, i.e. with 19 meters to 31 meters NEG pipes, striking similarities in pressure rise patterns have been observed.

In Fig.3, the pressure rises at pw3.1, pw3.2, and pw3.3 at Bo11 and Bi9, with 31 meters of NEG pipes, and Bo7, with 19 meters of NEG pipes are shown. The copper beam was injected, then dumped, injected and dumped again, then injected and accelerated through the beam transition. The pressure rise at pw3.1 was the highest, and that at pw3.2 was very low. The pressure at pw3.3 only rises around the transition.

The mechanism causing such pattern is under investigation. Incidently, all 7 such straight sections are with the beam toward, not from, interaction regions. It would be interesting to observe if there a difference at the straight sections where the beam is coming from interaction regions.

5 Saturated NEG pipes

The secondary electron yield rate of saturated NEG surface was measured to be around 1.3, at CERN and SLAC, which is much lower than a typical about 1.8 for a stainless steel surface, see references in [1]. With a saturated NEG pipe, therefore, the threshold of electron cloud should remain high.

The 31 meters of NEG pipes at the Blue straight section Bo11 was saturated carefully with dry nitrogen. In Fig.4, the pressure rise there for the Fills 7282 and 7283, after the saturation, is shown. Both injections were with 111-bunch mode and 0.8×10^{11} protons per bunch, ramped to 100 GeV. The ion pump at pw3.2 was turned off in Fill 7283, to identify the contribution of NEG pumping in the pressure rise.

The electron cloud induced pressure rise is low for both fills, and the pressure rise at pw3.2 is the lowest compared with pw3.1 and pw3.3. This is the same characteristics of the dynamic pressure rise in un-saturated NEG coated sections. Moreover, the pressure rise at pw3.2 was higher in 7283 than 7282, hence the contribution of the ion pump at pw3.2 is identified. The fact that the pressure rise at pw3.2 was still lower than pw3.1 and pw3.3 in 7283 may have demonstrated the effectiveness of saturated NEG coating in reducing electron cloud induced pressure rise.

In Fig.5, the comparison of the pressure rise at Bo11 for Fill 5350, in 2004 without NEG coating, and for Fill 7333, in 2005 with the saturated NEG, is show. When 55 bunches with 2×10^{11} protons per bunch injected in 5350, 2004, the pressure rise at Bo11 almost reached 10^{-7} Torr, with pw3.2 the highest. For the saturated NEG pipes in 7333, 2005, 111 bunches injected with 2.5×10^{11} protons per bunch, the highest pressure rise was 10^{-8} Torr at pw 3.3, and there was no pressure rise at pw3.2 at all.

Based on the effectiveness of saturated NEG coating in raising the electron cloud threshold, the requirement of re-activation of saturated NEG pipes in RHIC could be eased, which is in favor of lifetime of NEG coatings, and it also benefits in cost, labor and scheduling. The saturated NEG also has a potential application at the locations where in-situ activation is difficult or impossible.

6 Discussion

6.1 Effect on the beam

NEG coating helps to reduce the electron cloud induced pressure rise in three ways. First, NEG coating provides linear pumping. Second, NEG coating reduces SEY, and hence raises the electron multipacting threshold. Third, NEG coated surface has lower electron stimulated desorption rate [3], and hence for comparable electron dose on the chamber wall, fewer gas molecules are released.

The application of NEG coating helps the beam improvement in, similarly, two ways.

First, it eliminates the spots in the rings with highest dynamic pressure rise, and the beam with higher intensity can be allowed without causing vacuum valve closing and beam dump.

Second, the NEG coating helps to reduce/eliminate the electron multipacting. The electron cloud may affect beam in many ways, for example, it affects the beam coherent tune shift and incoherent tune spread, it may cause beam instability, and it may cause beam emittance blow-up. Most of these effect are not very clear for the RHIC operation under upgrade conditions at the moment, more beam studies are needed.

On the other hand, all these complications might be avoided at the first place, if NEG coating can be further applied.

6.2 Further application of NEG

In Fig.6, 4 each highest pressure rise locations of Blue and Yellow Q3-Q4 straight sections at pw3.2, and 4 interaction regions for the proton beam injection are shown for Fill 7136, which was with 111-bunch, 1.1×10^{11} protons per bunch.

The 4 interaction regions are, from highest pressure rise to lower ones, G4, G2, G12, and G10, with the peak pressure rise of 10^{-7}, 6.2×10^{-8}, 6.0×10^{-8}, and 5.7×10^{-8} Torr, respectively. For Yellow ring, similarly are Yo12, Yi7, Yo1, and Yo4, with 3.6×10^{-7}, 3.2×10^{-7}, 1.4×10^{-7}, and 1.1×10^{-7} Torr, respectively. For Blue, Bo2, Bi8, Bi12, Bo10, with 6.3×10^{-8}, 3.3×10^{-8}, 2.0×10^{-8}, and 1.3×10^{-8} Torr, respectively. It can be noticed that the Yellow ring has higher pressure rise compared with the Blue ring and the interaction regions as well.

The application of NEG pipes to the interaction regions is very difficult, due to the restrictions on the NEG activation. Several locations in single beam straight sections also have complications, such as Yo12 and Bi12 with polarimeters, and Yo4 with RF cavities, etc. Care must be taken in the applications of NEG coatings there.

It would be desirable to have the pressure rise reduced, especially in Yellow ring, in the coming 2006 polarized proton run, by installing more NEG pipes.

6.3 Possible concerns at RHIC

In two years' of NEG applications at RHIC, none of possible complications of NEG coating discussed beforehand [1] has caused serious concerns. These include,

- In-sufficient activation.
- Uncertainty in reductions of SEY and electron stimulated desorption of un-saturated and saturated NEG surfaces.
- Frequent need of re-activation.
- Damage of NEG coating with activation, saturation, venting, and other practices.
- Possible dust, aging, and others.

On the other hand, with more installations, longer time duration, and unavoidable machine maintenance and modifications, the issues such as the activation, re-activation, NEG coating's lifetime, etc. will require more attentions. In addition to careful analysis of RHIC operation and beam study data, the experimental data at Tandem test stand [2] can be invaluable to the RHIC practice decision making.

7 References

References

[1] S.Y. Zhang, H.C. Hseuh and T. Roser, 'NEG Coating at RHIC', C-A/AP/99, BNL, June 2003.

[2] P. Thieberger , J.G. Alessi, H. Abendroth, C. Carlson, H.C. Hseuh, L.P. Snydstrup, and S.Y. Zhang, 'First Results of Tandem beam induced desorption measurements for RHIC beam pipes', in preparation.

[3] P. Chiggiato, LHC/VAC/ChR/mpt, CERN, 2001

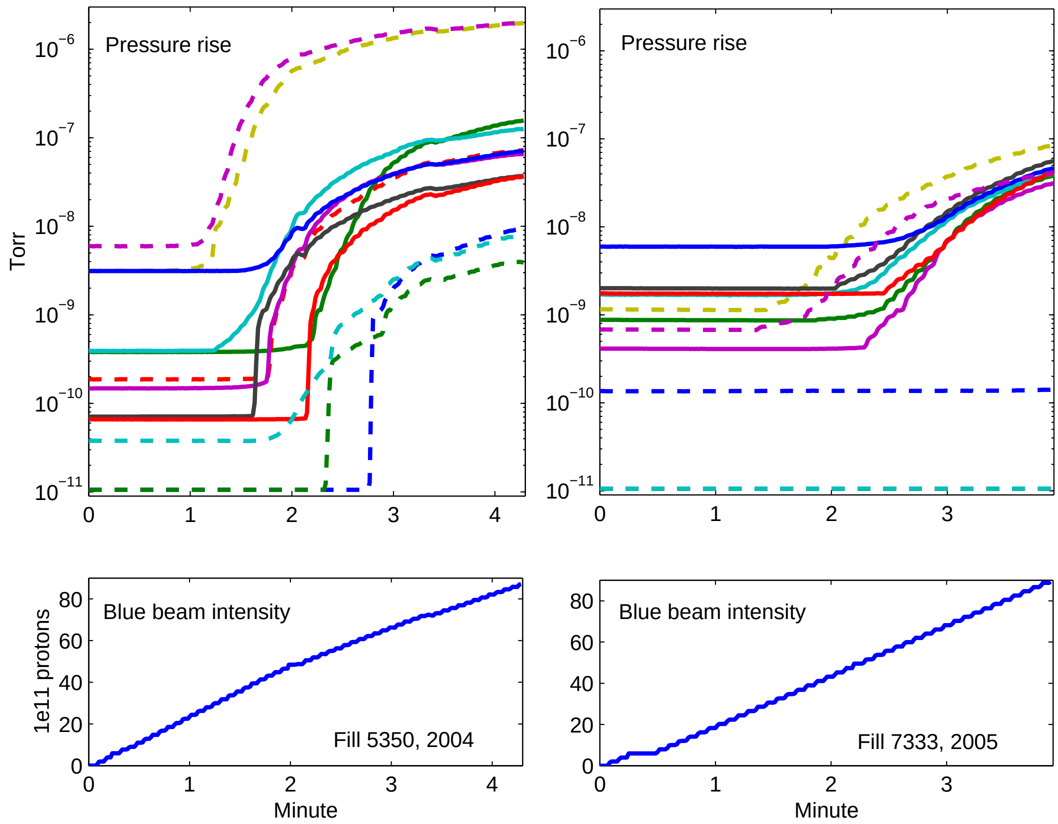

Figure 1: Pressure rises of Fill 5350 in 2004 and Fill 7333 in 2005. Both are Blue beams in 111-bunch mode (bunch spacing of 108 ns) and with 2×10^{11} protons per bunch. The pressure rises at pw3.2, located at the middle of the section, of all 12 Blue Q3-Q4 straight sections are compared. The two locations with highest pressure rises in 2004, i.e. Bi8 and Bo2, are much improved. All locations with NEG installations in 2005, in dotted lines, have shown improvements. All locations without NEG installation have about the same peak pressure rises in 2004 and 2005. The pressure levels prior to the beam injection in 7333, 2005, were high, which are the remnant from the beam injections occurred prior to this fill.

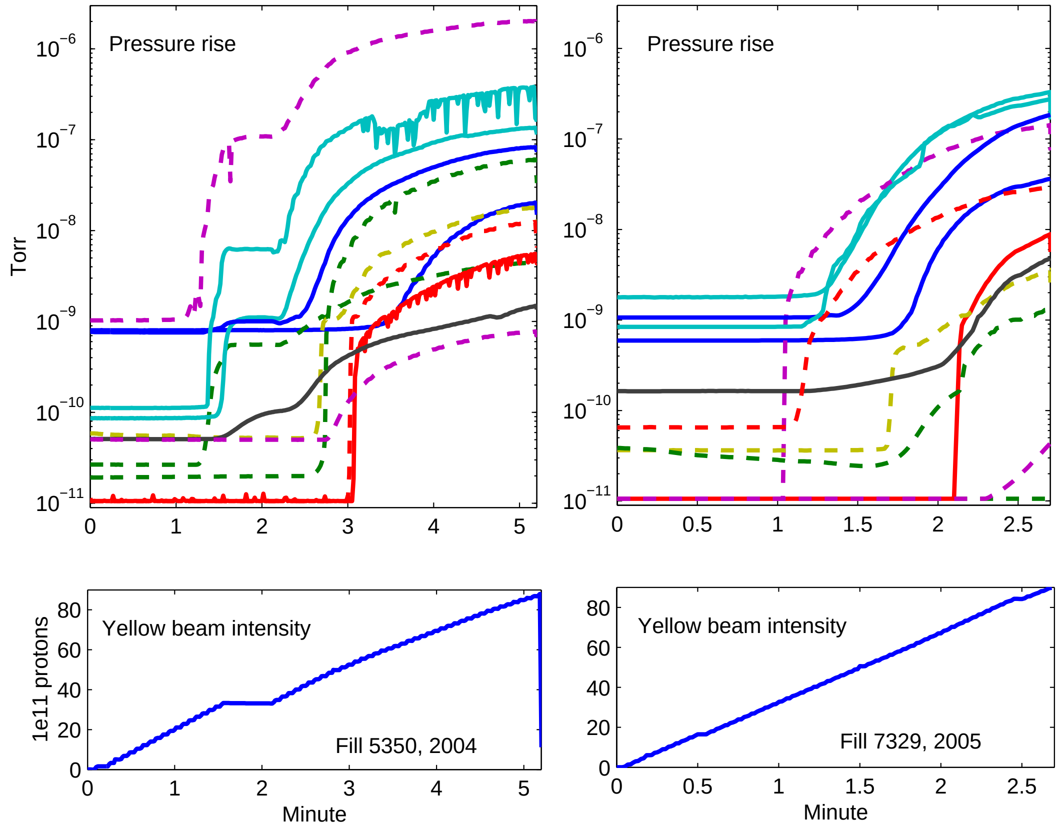

Figure 2: Pressure rises of Fill 5350 in 2004 and Fill 7329 in 2005. Both are Yellow beams in 111-bunch mode (bunch spacing of 108 ns) and with 1.5×10^{11} protons per bunch. The pressure rises at pw3.2 of all 12 Yellow Q3-Q4 straight sections are compared. The location with highest pressure rise in 2004, Yo1, are much improved, which is due to the NEG pipes. Most locations with NEG installations in 2005, in dotted lines, have improvement, but there are two exceptions. One is Yo4, where an ion pump close to pw3.2 was off in 2005 test (also the 7 meters of NEG pipes are close to pw3.3), and another is Yi6, where a new vertical collimator was installed (the NEG pipes are installed between pw3.1 and pw3.2). Most locations without NEG installation have about the same peak pressure rises in 2004 and 2005. One exception is Yo5, where the anti-grazing ridges were installed for beam testing.

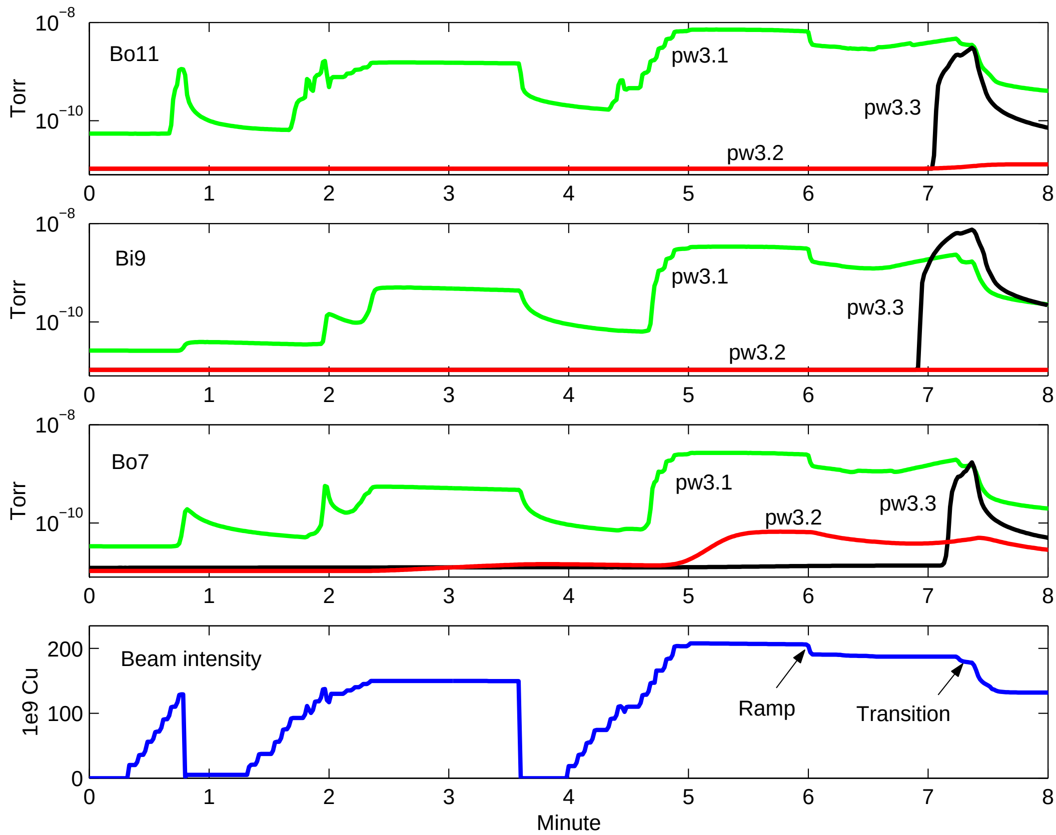

Figure 3: Striking similarities of pressure rise in fully and largely NEG covered single beam straight sections, at Bo11 and Bi9, with 31 meters of NEG pipes, and Bo7, with 19 meters of NEG pipes. pw 3.1 are at the end of straight sections close to interaction region, pw 3.3 at the other end, and pw 3.2 is in the middle. The copper beams were injected, then dumped, injected and dumped again, then injected and accelerated through the beam transition. The pressure rise at pw3.1 was the highest, and that at pw3.2 was very low, where is usually the highest for straight sections without NEG pipes. The pressure at pw3.3 only rises around the transition. The pressure rise pattern for proton runs is also similar to each other for these NEG covered sections.

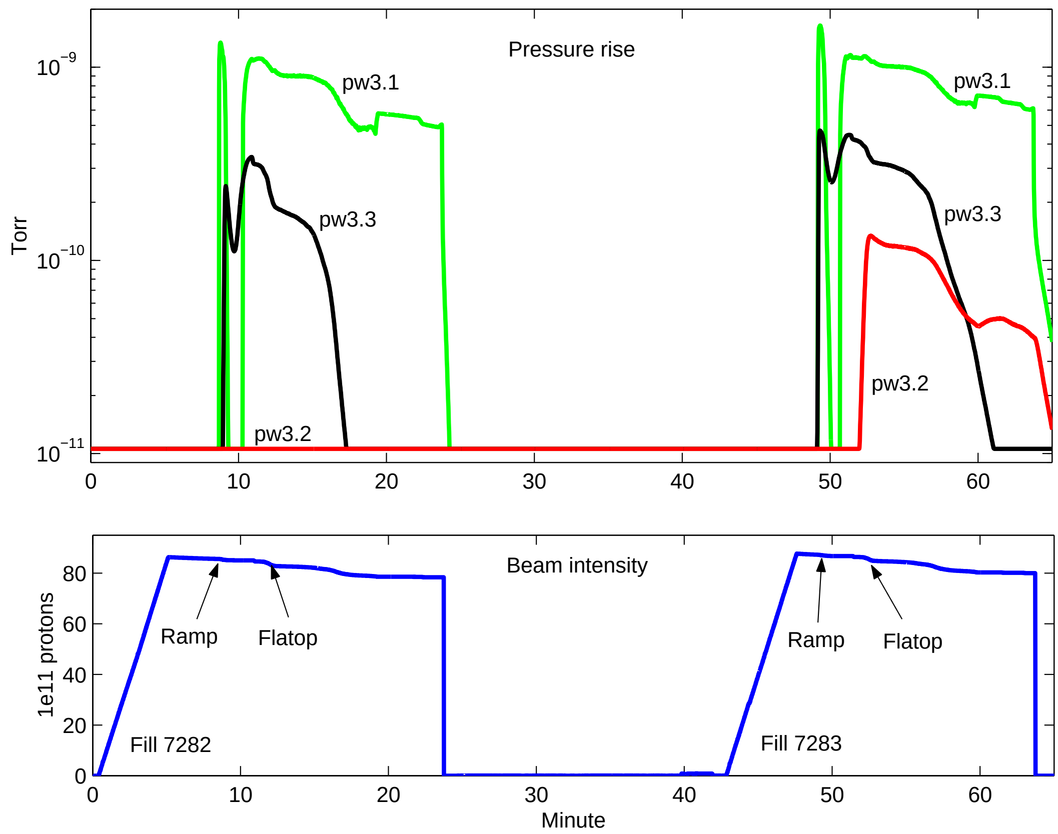

Figure 4: Pressure rise at Bo11, with 31 meters of saturated NEG pipes. Two fills of 7282 and 7283 are with 0.8×10^{11} protons per bunch, 111-bunch mode, with energy ramp to 100 GeV, followed by a rotator ramp. The ion pump at pw3.2 was turned off in 7283. In both cases, the pressure rises at pw3.2 are the lowest compared with that at pw3.1 and pw3.3. This pattern is similar to that observed for un-saturated NEG pipes, indicating that the saturated NEG coating remains to be effective in reducing the electron cloud induced pressure rise.

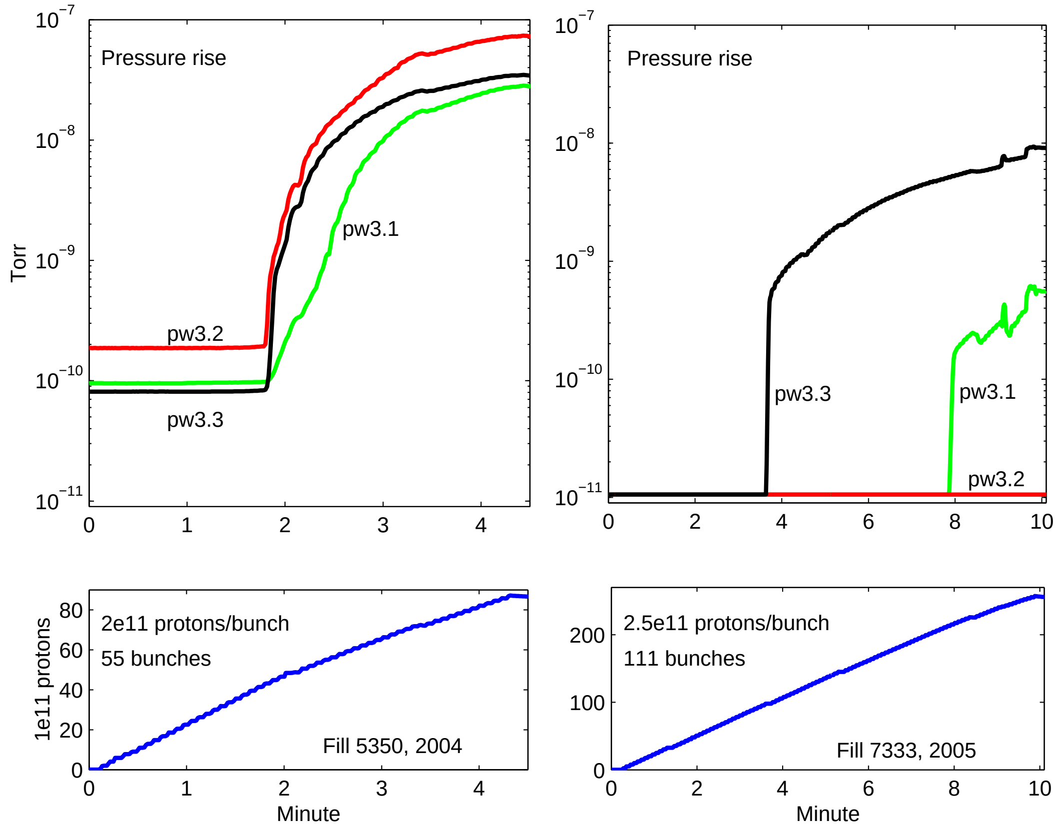

Figure 5: Comparison of the pressure rise at Bo11 for Fill 5350, in 2004 without NEG coating, and for Fill 7333, in 2005 with the saturated NEG, is show. When 55 bunches with 2×10^{11} protons per bunch injected, the pressure rise at Bo11 almost reached 10^{-7} Torr, with pw3.2 the highest in 5350, 2004. For the saturated NEG pipes in 7333, 2005, 111 bunches injected with 2.5×10^{11} protons per bunch, the highest pressure rise was 10^{-8} Torr at pw 3.3, and there was no pressure rise at pw3.2 at all.

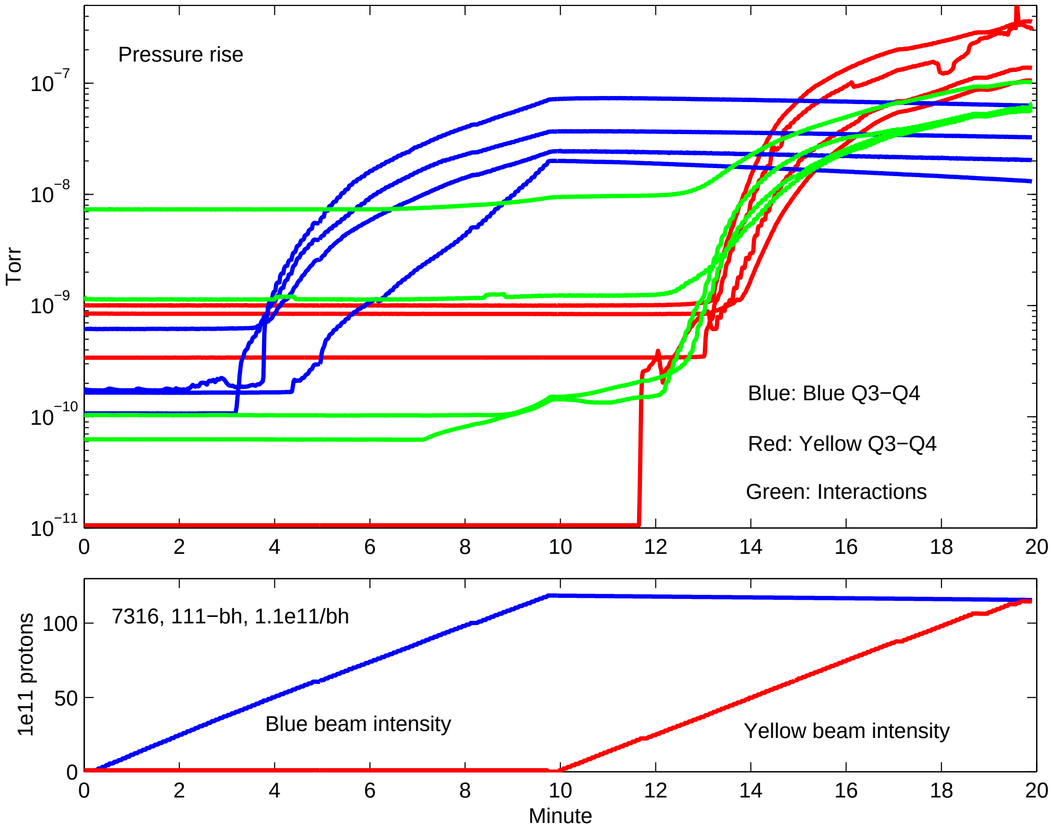

Figure 6: 4 each highest pressure rise location of Blue and Yellow Q3-Q4 straight sections at pw3.2, and 4 interaction regions with highest pressure rise are shown. The proton beam injection is Fill 7136, with 111-bunch, 1.1×10^{11} protons per bunch. The 4 interaction regions are, from highest pressure rise to lower ones, G4, G2, G12, and G10, with the peak pressure rise of 10^{-7}, 6.2×10^{-8}, 6.0×10^{-8}, and 5.7×10^{-8} Torr, respectively. For Yellow ring, similarly are Yo12, Yi7, Yo1, and Yo4, with 3.6×10^{-7}, 3.2×10^{-7}, 1.4×10^{-7}, and 1.1×10^{-7} Torr, respectively. For Blue, Bo2, Bi8, Bi12, Bo10, with 6.3×10^{-8}, 3.3×10^{-8}, 2.0×10^{-8}, and 1.3×10^{-8} Torr, respectively. Note that these 4 Yellow sections have highest pressure rises in RHIC.