ELECTRON CLOUD OBSERVATIONS AND CURES IN RHIC*

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Abstract

Since 2001 RHIC has experienced electron cloud effects, which have limited the beam intensity. These include dynamic pressure rises – including pressure instabilities, tune shifts, electrons, a reduction of the stability threshold for bunches crossing the transition energy, and possibly slow emittance growth. We summarize the main observations in operation and dedicated experiments, as well as countermeasures including baking, NEG coated warm beam pipes, solenoids, bunch patterns, anti-grazing rings, pre-pumped cold beam pipes, and scrubbing. This article is a condensed version of Ref. [1].

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC), in operation since 2000, has collided species from polarized protons, at energies up to 100 GeV, to gold ions, at energies up to 100 GeV/n. Since 2001 dynamic pressure rises were observed that limit the beam intensity. At that time the cause of the dynamic pressure rise was not known. As possible causes were considered: electron impact desorption after electron cloud formation, ion-impact desorption after restgas ionization and ion acceleration in the beam potential, and beam loss induced desorption [2]. It was later concluded that all operationally relevant pressure rises can be explained by electron clouds. Tab. 1 shows selected machine and beam parameters relevant to electron clouds for all species operated in RHIC so far.

Table 1: Main machine and beam parameters relevant to electron clouds for all species RHIC has operated with [3].

parameter	unit	Au	Cu	d	p
atomic number Z	...	79	29	1	1
mass number A	...	197	63	2	1
revolution time T_{rev}	μs	12.8			
harm. no. h, accel.	...	360			
harm. no. h, store	...	2520			360
full bunch length, inj.	ns	15			20
full bunch length, store	ns	5			10
no. of bunches N	...	up to 111			
bunch spacing t_b	...	multiples of 108 ns			
ions per bunch N_b	10^9	1.1	50	110	200

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OBSERVATIONS

Dynamic pressure rise

Dynamic pressure rise from electron-impact desorption after an electron cloud has been formed was the first, and still is the most common electron cloud observation in RHIC [2, 4, 5]. It is also the operationally most relevant electron cloud effect in RHIC. This pressure rise is particularly pronounced at transition crossing when the ion bunches are short [6, 7]. In some cases the electron cloud switched off spontaneously, like in a second order phase transition [8], which can be explained if the both and electron and ion cloud is assumed [9].

Pressure instabilities

In some instances pressure instabilities could be observed, where the pressure growths exponentially without bounds until the beam is aborted by the beam permit system. This occurred with gold beam, in unbaked locations, and after an electron cloud was formed. The formation of an electron cloud can be triggered after the bunch length is reduced, when, for example, bunches are transferred from the accelerating rf system into the storage rf system. An analysis shows that such an instability is possible for gases like CO [10, 11].

Tune shift

The observation of the coherent tune shift along a bunch train was the second electron cloud observation [12]. The sign of the observed tune shift in both planes is consistent with the existence of electron clouds, and the value of the tune shift allowed a first estimate of the electron cloud density, making comparisons with simulations possible [12, 13].

Electrons

Shortly after the first electron cloud observations were made, a number of electron detectors were installed [14, 15]. These allowed a direct observation of the electron cloud build-up, allowed correlations with the observed dynamic pressure rise, and were used to measure the energy distribution of the electrons in the cloud, and electron-impact desorption coefficients [16, 17].

Beam instabilities

In RHIC, all species, except protons, cross the transition energy. Because the main magnets are superconducting, their ramp rate is slow, and transition crossing is facilitated with a γ_t-jump of fast ramping quadrupoles. However, the short bunch length near transition can lead to instabilities. These are single bunch, transverse, and have growth times as low as 15 ms [18]. It was found that electron clouds, also enhanced by the short bunch length, can reduce the stability threshold. This manifests itself through increasing beam loss along the bunch train [19].

Emittance growth

Incoherent emittance growth from electron clouds was investigated in Refs. [20–22]. In the most recent polarized proton run, bunches shortened through rf quadrupole pumping in the AGS were injected into RHIC, in order to increase the luminosity through the reduction of the hourglass effect at store. However, the luminosity of the stores with bunches of reduced length was lower than the luminosity of stores with longer bunches of comparable intensity [23]. At the same time, a higher dynamic pressure was observed at injection. This could be an indication that electron clouds at injection have increased the proton beam emittance. In a separate test the emittance growth of proton bunches at injection was observed, and exceeded expectations from intra-beam scattering.

CURES

In-situ baking

The RHIC beam pipes in the warm regions are made of stainless steel 316LN. At the manufacturer the drawn tubes were detergent cleaned, water rinsed, acid prickled with $HF+HNO_3$, water rinsed again, annealed at 1050°C for 10 min, and then quenched. At BNL the pipes were cut to length, the end flanges welded, then baked under vacuum for 350°C for 24 h. Pipes for installation in magnets were leak checked and sealed before delivering to the magnet manufacturer.

Due to scheduling constraints the warm beam pipes were not baked in-situ initially. After the first dynamic pressure rises were observed, a program was started to bake in situ all warm pipes. With the exception of a few instruments, and the warm rf, this is possible at all other locations. This program yielded the first significant increase in the beam intensity.

NEG coating

To reduce the dynamic pressure rise, solenoids and NEG coated beam pipes were tested in small sections. For large scale installation in the warm beam pipes, NEG coating was chosen because, at comparable cost, the same or better electron cloud suppression was observed with NEG coating, which also provides distributed pumping [24,25]. Note that dynamic pressure rises is the main electron cloud effect in RHIC.

Solenoids

Up to 64 m of solenoids were installed for evaluation purposes. These showed a reduction of the observed electron cloud, and the pressure rise, at fields of 1.2 mT. However, the electron cloud could not be suppressed completely with fields up to 2.7 mT. Solenoids are still used near some experimental areas, and some equipment that cannot be baked at high temperature.

Bunch patterns

When machines are operated with less than the maximum number of bunches, the flexibility of rearranging the intensity in different bunch patterns can be used to minimize the electron cloud density. For the RHIC parameters we concluded that the electron cloud is minimized, and at the same time the luminosity maximized, when a given total intensity can be distributed in as few bunches as possible, which are uniformly distributed around the circumference [26]. This problem lends itself to analysis through maps for electron clouds [27]. Optimized bunch patterns were used in the RHIC runs in 2004 (Au-Au) and 2005 (Cu-Cu), when the number of bunches was reduced as more bunch intensity became available. These runs were limited by dynamic pressure rises in the PHOBOS experiment, that lead to unacceptable experimental background [8].

Anti-grazing rings

Lost beam particles hitting the beam pipe under a grazing incident angle, penetrate the beam pipe surface many times due to the surface roughness. This is expected to lead to electron and molecular desorption coefficients one to two orders of magnitude higher than for perpendicular impact. In Ref. [28] a mitigation was proposed by installing anti-grazing rings, through which all particles are lost with near perpendicular impact. Such grazing rings were installed in 2 sections in RHIC, and a reduction in the dynamic pressure rise could be observed [29]. However, for the grazing rings to be effective, they must intercept beam, which can lead to increased experimental background if they are close to a detector. With the large-scale installation of NEG coated beam pipes, currently, no anti-grazing rings are installed in RHIC.

Pre-pumping in cold sections

At high proton beam intensities an increase in the gas density in the cold sections was observed. The cold sections relied on cryo-pumping, and had been evacuated to about 10^{-1} Torr only in some areas, leading to up to 100 mono-layers of gas on the wall surface. After the observation of an increased gas density in the cold arcs, more pumps were installed in these regions, which evacuated the beam pipe to 10^{-6} to 10^{-7} Torr before cool-down of the magnets, leading to much less than a mono-layer of gas on the cold beam pipe surface. With this no further increases in the gas density were observed.

Scrubbing

Scrubbing had been tested first in 2004 [30]. With scrubbing times of a few hours a reduction of the dynamic pressure rise by some 10% was observed in locations with the highest pressure. Scubbing is most efficient in locations with large dynamic pressure rises. At the beginning of the 2007 gold-gold run pressures up to 10^{-6} Torr were observed near the warm rf and a few other locations that can not be baked at high temperature. Two hours of scrubbing at injection with the highest available ion intensities, and seven fills, reduced the dynamic pressure by approximately one order of magnitude at the locations with the highest pressure.

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