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Electron Cloud Phase Transitions

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Abstract

How do electron clouds go through the transition from "on" to "off"? Experimental data from RHIC show both first order phase transitions (near the PHOBOS experiment at interaction point IP10) and also second order transitions (for example near IP12). Simulations show behavior that conforms to the generic power law form expected for second order phase transitions, but with different exponents from those observed in RHIC. A simple theoretical map model shows generic second order phase transition power law behavior, with an arbitrary exponent.

1 First and second order phase transitions

The hallmark of a first order phase transition is the discontinuity in both the value and in the first differential of a dependent quantity, as an independent variable passes a critical value. For example, there is no penetration of magnetic flux B into a Type I superconductor as the applied field H is increased, until a critical field H_C is passed. Above this field there is full flux penetration, so that

$$B = 0 \qquad H < H_C \tag{1}$$
$$B = \mu H \qquad H > H_C \tag{2}$$

where μ is a constant. Another example of a first order phase transition is the coherent center-of-charge response of a beam to an AC dipole excitation as the tune of the AC dipole is adiabatically scanned across the free betatron tune, in the presence of anharmonicity. The coherent signal suddenly drops to zero when the driven stable fixed point disappears.

There is a discontinuity only in the slope of the independent quantity if the phase transition is second order; the independent quantity is piecewise continuous. Second order phase transitions often follow a universal "power law" functional form. Thus, if the electron cloud density ρ exhibits a second order phase transition in going from "on" to "off" as the single bunch population N is varied, it is reasonable to expect on general grounds that

$$\rho = 0 \qquad N < N_C \tag{3}$$
$$\rho \approx \alpha\,(N - N_C)^{\beta} \qquad N > N_C \tag{4}$$

where the coefficients α and β depend on the details of the physics. The approximation is valid for values of N in the vicinity of N_C. Now add the assumption that the bunch population decays at an approximately constant smooth rate dN/dt near the time T_C at which it crosses the critical population N_C, so that

$$N \approx N_C + \frac{dN}{dt}(t - T_C) \tag{5}$$

In this case the decay of the electron cloud is also expected to follow a universal form

$$\rho(t) \approx \alpha \left(\frac{dN}{dt}(t - T_C) \right)^{\beta} \tag{6}$$

The population decay rate may be due to natural effects in storage, or it could be deliberately enhanced in a controlled experiment to measure α and β simultaneously at many locations around a ring. In this case it is perhaps more convenient to make the right hand side linear in time t by writing

$$\rho(t)^{1/\beta} \approx \alpha^{1/\beta}\,\frac{dN}{dt}\,(t - T_C) \tag{7}$$

Thus the electron cloud density is expected to decay smoothly until it reaches zero and the cloud turns "off" – if the electron cloud phase transition is second order.

In stark contrast, a first order phase transition leads to a sudden and dramatic disappearance of the electron cloud, as the bunch population decays away smoothly. The experimental signature of the electron cloud density – or its surrogate, the vacuum pressure – "falling off a cliff" is routinely observed near the PHOBOS experiment in RHIC during gold ion stores [1].

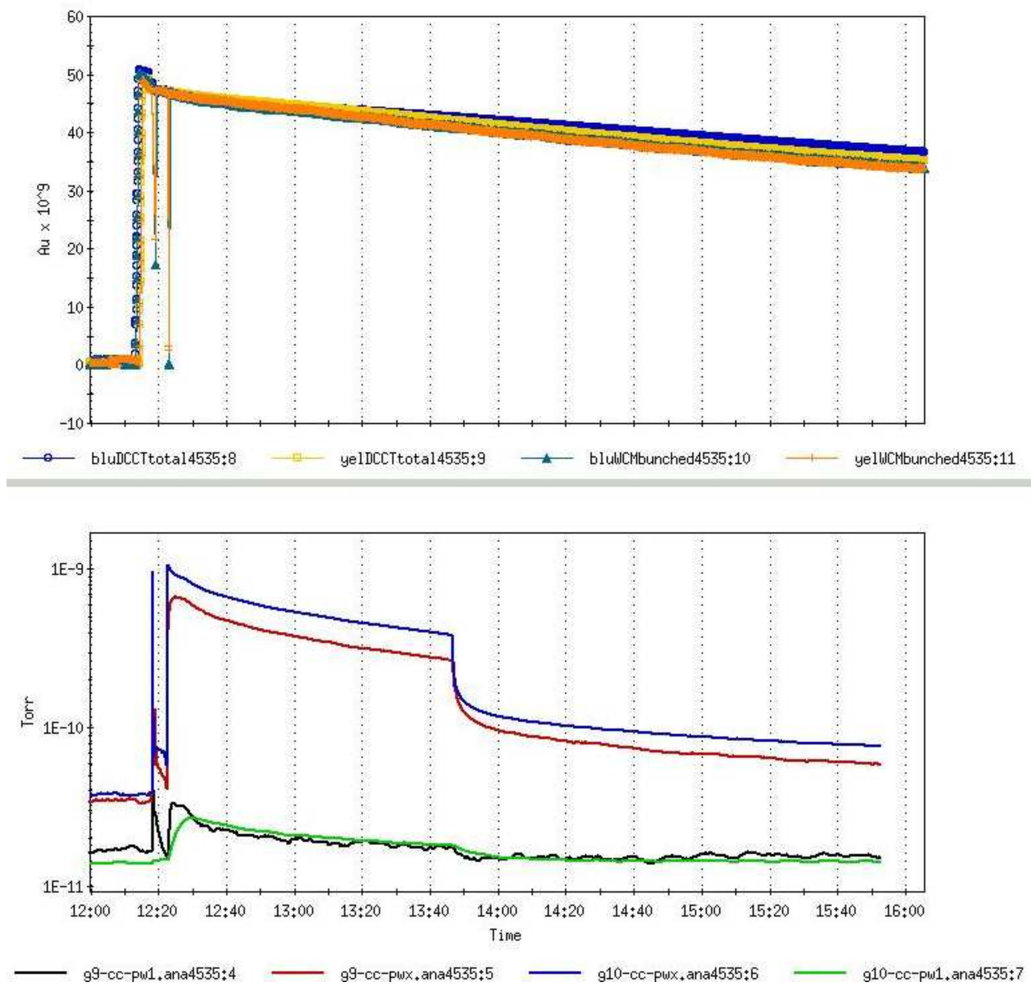

Figure 1: Vacuum pressure evolution in the common Beryllium beam pipe near PHOBOS during Fill 4535 (February 14, 2004). The top plot shows the total beam population in Blue and Yellow rings, while the bottom plot logs the pressure measured by two gauges, during a store of almost 4 hours. The pressure suddenly drops at about 13:35, indicating a first order phase transition from electron cloud "on" to "off".

2 Observations of electron cloud phase transitions in RHIC

2.1 First order phase transitions near PHOBOS in IP10

Figure 1 shows typical behavior of the vacuum pressure near Interaction Point 10 during a routine 4 hour gold ion store in 2004 [1]. Both Blue and Yellow beams circulate in the same "common" beam pipe that passes through the PHOBOS experiment, where the measurements were made. At about 13:55 there is a sudden and dramatic drop in the vacuum pressure – and, by inference, in the electron cloud density. This indicates that a first order phase transition has been crossed.

Figure 2 plots pressure versus total beam population for the data shown in Figure 1. It is assumed that the single bunch population N is proportional to the total population, so that this curve represents (ρ, N) phase space. The beam pressure drops from about 0.4 nTorr to less than 0.1 nTorr at the phase transition.

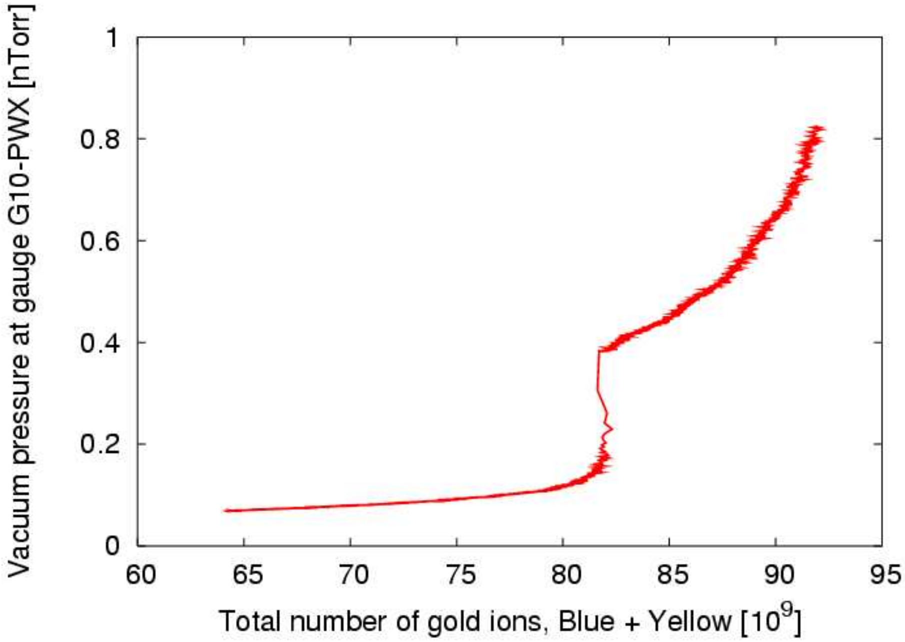

Figure 2: Vacuum pressure versus total beam population during RHIC Fill 4535 (February 14, 2004). A first order electron cloud phase transition is clearly visible – assuming that vacuum pressure and total population are valid surrogates for electron cloud density ρ and single bunch population N. Each ring contains 56 bunches spaced by 216 ns with an average bunch population of about 0.8×10^9 gold ions, followed by 4 "empty bunches" in an abort gap.

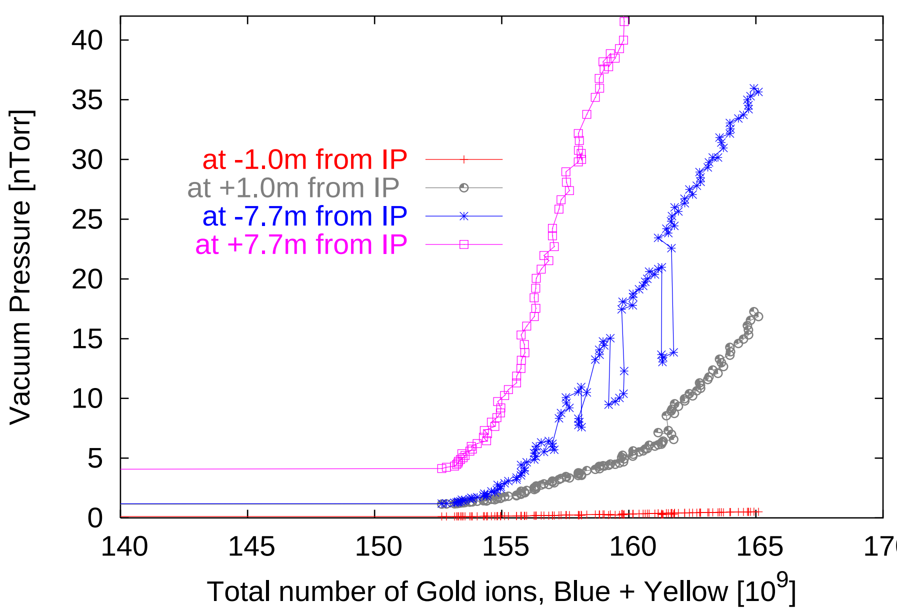

Figure 3: Vacuum pressure versus total beam population at four locations in the common beam pipe near Interaction Point 12 during Fill 4794 (March 17, 2004). All four curves imply a nearly linear dependence of electron cloud density ρ on single bunch population N, demonstrating second order phase transition behavior. Spurious dips in one or two of the plots are due to an electron cloud suppression solenoid being turned on and off. Each ring contains 110 bunches spaced by 108 ns with an average bunch population of about 0.7×10^9 gold ions, followed by 10 "empty bunches" in an abort gap.

2.2 Second order phase transitions near IP12

Figure 3 shows vacuum pressure versus beam population at four locations in a common beam pipe near Interaction Point 12, during a typical store. All four measurements show second order phase transition behavior, insofar as there is no sudden transition from "on" to "off", at least over the range of available data. Pressure rises at the four vacuum gauges span more than two orders of magnitude, due to their varying distances from the interaction point. One of the curves shows two or three "spurious" drops in pressure (and electron cloud density) when a solenoid wrapped around the beam pipe at that location is briefly turned on. These data suggest electron clouds that are well fit at relatively large densities by straight lines ($\beta \approx 1$):

$$\rho = 0 \qquad N < N_C \tag{8}$$

$$\rho \approx \alpha\,(N - N_C) \qquad N > N_C \tag{9}$$

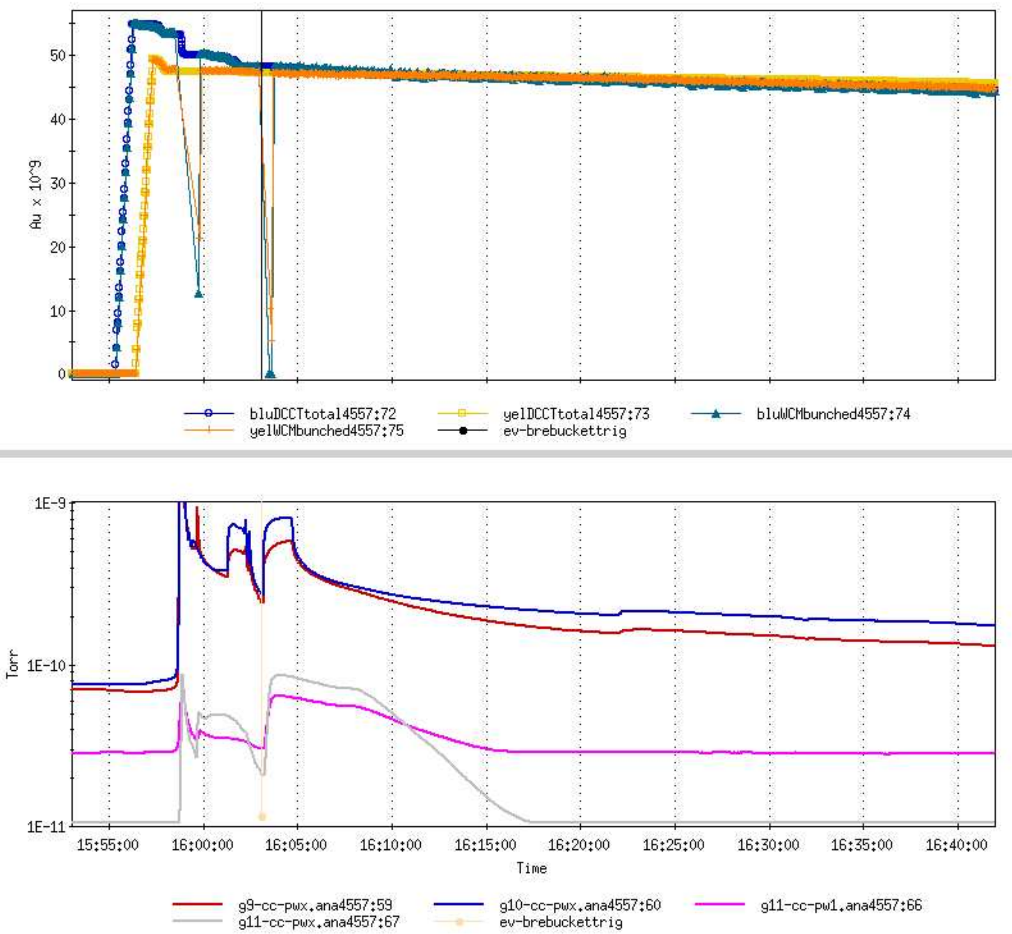

Figure 4: Vacuum pressure evolution near both IP10 and IP12 during Fill 4557 (February 17, 2004). Electron clouds turn on immediately after RF re-bucketing shrinks the full bunch length to about 4.5 ns at 16:03. The electron clouds at IP10 suddenly disappear at about 16:05, demonstrating a first order phase transition. Electron clouds at IP12 decay smoothly until they turn off at around 16:16, in typical second order fashion. Each ring contains 56 bunches spaced by 216 ns with an average bunch population of about 0.8×10^9 gold ions, followed by 4 "empty bunches" in an abort gap.

2.3 A store with both first and second order electron cloud transitions

Figure 4 shows both first order (near IP10) and second order (near IP12) electron cloud transitions at different times during the same store. Beam is re-bucketed at top energy into higher frequency RF buckets at about 16:03, as indicated by the vertical marker. The associated reduction in bunch length turns on the electron cloud near both interaction points, only to have it suddenly turn off at IP10 in typical first order fashion two minutes later, at about 16:05. In contrast the electron cloud at IP12 decays smoothly over about 10 minutes, until it turns off at about 16:16. There is an unexplained knee in the rate at which the IP12 cloud decays, at about 16:08.

Figure 5 re-plots this behavior for the post re-bucketing data, showing the first order transition at IP10 (top graph) and the second order behavior at IP12 (bottom graph).

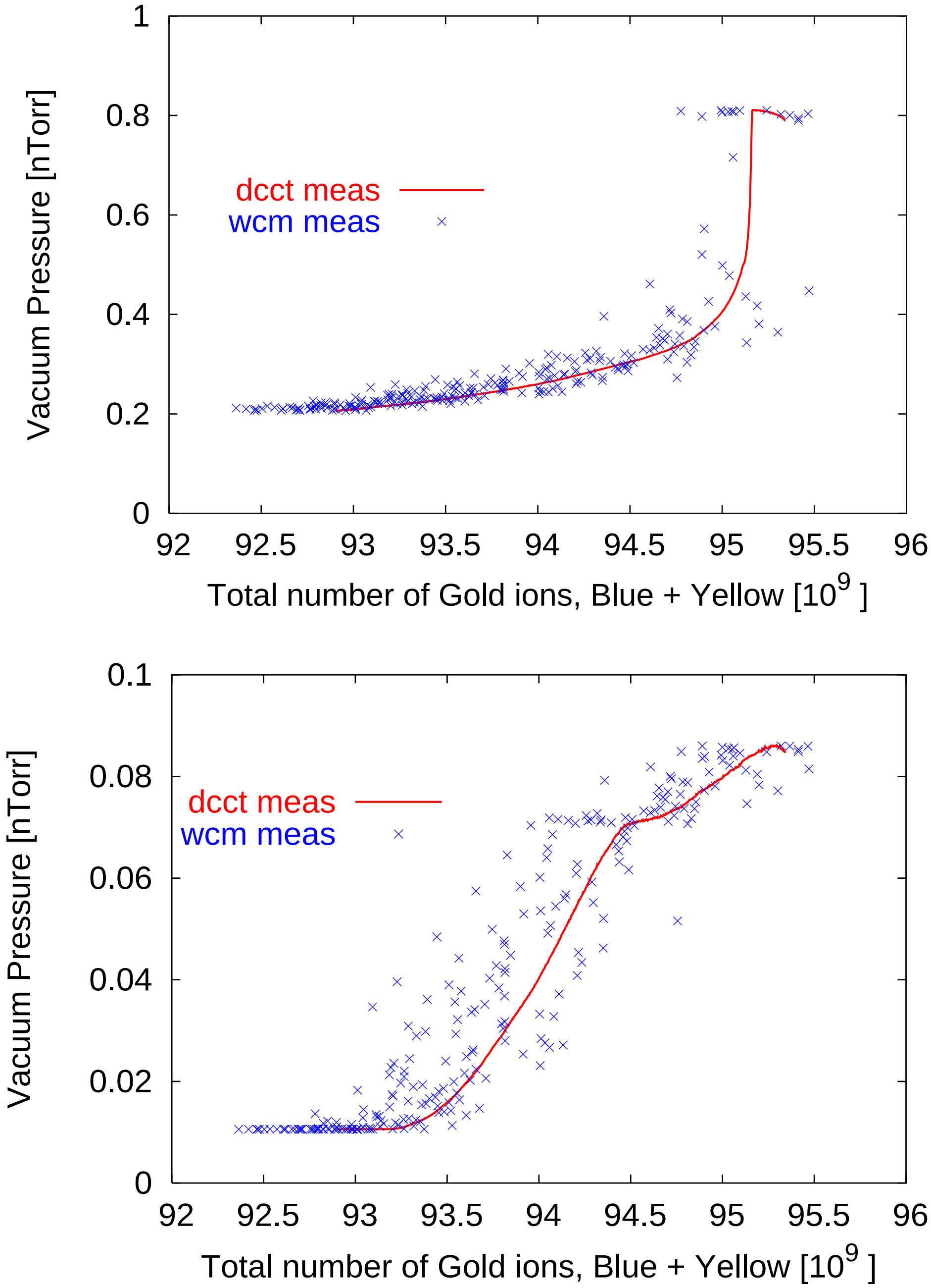

Figure 5: First and second order electron cloud phase transitions observed, respectively, in IP12 (top) and in IP10 (bottom). Both wall current monitor (WCM) and direct current current transformer (DCCT) measures of the total bunch population are shown.

3 Simulation results showing second order transitions

Figure 6 shows the results of an investigation of the electron cloud phase transition using the simulation CSEC [2]. While the simulation conditions and parameters are somewhat similar to those in the RHIC observations, there are significant differences. For example, there is only one beam in the simulation, with 120 bunches and no abort gap. The results shown here are for a 6 cm radius beam pipe with a maximum secondary emission yield of $\delta_{MAX} = 2.3$, a typical value for unbaked stainless steel. The full length of the parabolic bunch is 18 ns.

The curve in Figure 6 represents a power law fit to the data. Using the notation described in Equation 4, the fit parameters are

$$\alpha = 0.044 \pm .012 \quad (10)$$

$$\beta = 0.509 \pm .017 \quad (11)$$

$$N_C = 7.398 \pm .005 \quad (12)$$

The CSEC simulation strongly suggests a square root behavior, with $\beta = 1/2$, inconsistent with the approximately linear behavior shown by the second order RHIC observations, with $\beta \approx 1$. One open question concerns the extent of the universality of this square root behavior: how many simulation codes does it hold for, over how broad a range of physical parameters?

It seems unlikely (although it is not impossible) that CSEC can also exhibit first order electron cloud phase transitions, such as those routinely seen near PHOBOS. It also seems unlikely that other simulation codes will reproduce first order transitions, unless they include additional physics that is apparently present, at least at some locations, in real life.

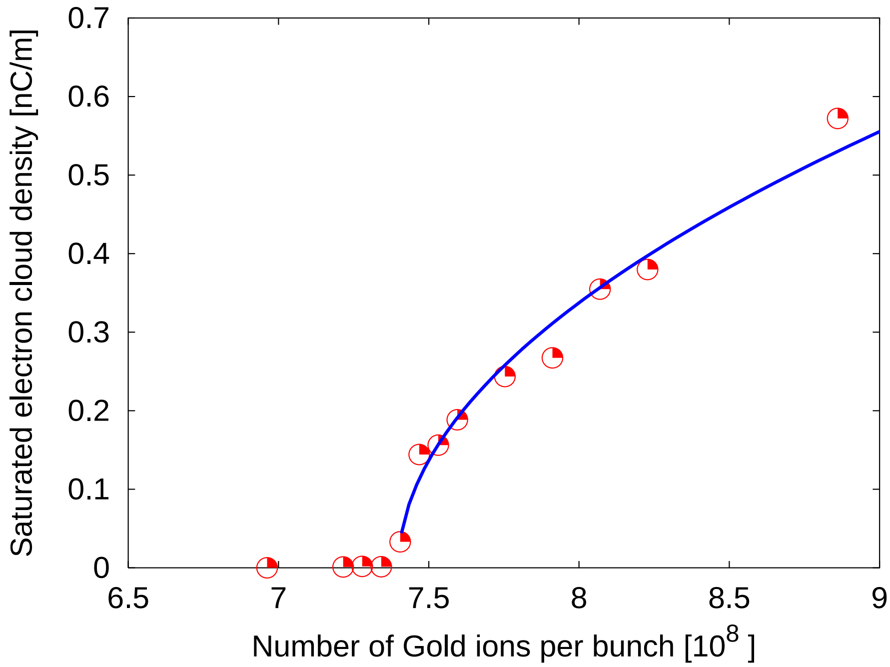

Figure 6: Simulation results from the simulation code CSEC, showing a second order phase transition with a square root power law turn on. The curve is a fit to the data, with exponent $\beta = 0.509 \pm 0.017$.

4 Theoretical map model showing second order phase transitions

Electron cloud evolution can be theoretically described by a map model in which the average (or sampled) electron density evolves during the passage of bunch i through

$$\rho_{i+1} = M(\rho_i, N_i) \tag{13}$$

where N_i is the population of bunch i, and M is the mapping function [3]. Such maps implicitly assume that it is legitimate to neglect previous history, such as the population of previous bunches N_{i-1}, et cetera. This assumption may or may not be reasonable in a particular situation. However, the goal here is not to legitimize maps, although they have been shown to work for typical RHIC parameters with regularly spaced bunches [3]. The goal here is rather to show how elegantly a simple binomial map leads to second order phase transitions in the general power law form.

Assume that a binomial map

$$\rho_+ = (1 + a_1)\rho - a_m \rho^m \tag{14}$$

describes the evolution of the electron cloud density from one bunch passage – or turn – to the next. The coefficients a_1 and a_m are functions of the bunch population N, while the exponent m is assumed to be larger than 1, but is otherwise left free. Electron cloud saturation occurs when

$$\rho_+ = \rho \equiv \rho_S \tag{15}$$

that is, when

$$\rho_S = \left(\frac{a_1}{a_m}\right)^{1/(m-1)} \tag{16}$$

Consider a range of bunch populations near the critical population N_C at which the electron cloud collapses

$$a_1(N_C) = 0 \tag{17}$$

$$\rho_S(N_C) = 0 \tag{18}$$

In a narrow enough range around N_C a linear approximation holds for the linear map coefficient a_1

$$a_1 \approx b_1 (N - N_C) \tag{19}$$

while the (positive) coefficient a_m is approximately constant

$$a_m \approx a_m(N_C) \equiv a_{mC} \tag{20}$$

Thus the phase transition from electron cloud "on" to "off" is consistent with the behavior described in Equation 4, with coefficients

$$\beta = \frac{1}{m-1} \tag{21}$$

$$\alpha = \left(\frac{b_1}{a_{mC}}\right)^{\beta} \tag{22}$$

As promised, a simple binomial map reproduces the general power law form of a second order phase transition.

If (for example) $m = 3$ then

$$\rho_S \approx \alpha(N - N_C)^{0.5} \qquad N > N_C \tag{23}$$

consistent with the CSEC simulation results. In contrast, RHIC observations suggest $\beta \approx 1$, supporting an exponent $m \approx 2$.

5 Summary

Observations in RHIC show both first order and second order electron cloud phase transitions. The second order phase transition data suggest an exponent of $\beta \approx 1$ in the generic power law form.

Simulations with CSEC show only second order electron cloud phase transitions with $\beta = 0.509 \pm 0.017$, inconsistent with RHIC observations. It is not yet known whether other simulation codes also generate such "square root" second order phase transitions. It seems unlikely that any contemporary simulation code also reproduces first order electron cloud phase transitions. New physics needs to be included in the codes, in order to simulate the first order transitions routinely observed in the Beryllium beam pipe that passes through the PHOBOS experiment in RHIC.

Theoretical map models readily reproduce second order electron cloud phase transitions, with arbitrary power law exponents. This is necessary to legitimize map models, but it is not sufficient to guarantee their applicability in all cases.

6 Acknowledgments

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References

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[2] *Electron cloud measurements and simulations for the Brookhaven Relativistic Heavy Ion Collider*, W. Fischer, M. Blaskiewicz, M. Brennan, T. Satogata, PRST-AB 5, 124401 (2002).

[3] *Electron Couds at RHIC*, U. Iriso, http://www.agsrhichome.bnl.gov/LARP/030916_danfords/Iriso.pdf ; Presentation by U. Iriso in the proceedings of ECLOUD04; U. Iriso, forthcoming C-AD/AP note (2004).