Dynamic Electron Cloud Modeling

Report compiled by Sumner Hearth

September 9, 2016

Notice

This report is subject to frequent changes, and may not always be up-to-date with the most recent version of the simulations. Below I will include a list of changes not yet accounted for:

- Offset effects have not been updated to newest lattice file [cta_2085mev_xr20m_20151208.lat]
- Pinching has not been updated to newest lattice file [cta_2085mev_xr20m_20151208.lat]

1 Goal

The goal of this project is to produce a bmad plugin that correctly emulates the bunch growth and tune shifts seen in experiments using a dynamic electron cloud. The electron cloud is modeled as a gaussian charge distribution with dynamic position $\overrightarrow{\mu} = (\mu_x, \mu_y)$ and total charge q.

For now all the computation described below is only applied to lattice elements representing dipole bends.

2 Modeling

2.1 Static Cloud

Consider first a static cloud with no bunch growth, translation, or pinching. The cloud in this scenario is modeled as a gaussian distribution with parameters q, σ_x, σ_y, referring to *total charge*, and x and y variance respectively. The program is written into a Bmad `track1_postprocess` module which means it is applied to each particle at the end of each lattice element. As a particle enters we determine whether the particle belongs to a new bunch, or is another particle in the current bunch. This is determined based on the current time of the particle versus the time of the last seen particle. If that time exceeds half the expected inter-bunch time ($\frac{14ns}{2}$) then it is considered to be a new bunch. The kick applied to the particle is then calculated using bmad's `bbi_kick` procedure. We supply to it the relative distance of the particle (from `end_orb`) and the $\frac{\sigma_x}{\sigma_y}$ ratio. This gives us a relative kick value in either dimension which we must scale by a factor `bbi_const`. This constant is determined by $\frac{q}{(2\pi\gamma(\sigma_x+\sigma_y))}$. This is not directly as stated in the documentation, which states

bbi_const = N_particles_bunch * e_charge / (2 * pi * gamma * (sig_x + sig_y))

However so long as it is maintained that the charge `q = N_particles_bunch * e_charge` then this should be fine. This constant times the relative kick values gives the change in momentum in radians, which is added to the particle passing through the lattice element.

For a particle with given $(\overrightarrow{x}, \overrightarrow{p})$ and cloud $(\overrightarrow{\mu}, \overrightarrow{\sigma})$ in a lattice element with length (s) we update the particle characteristics as follows:

$$\vec{k} = \text{bbi\_kick}\left(\frac{x - [\vec{\mu}_i]_x}{\sigma_x}, \frac{y - [\vec{\mu}_i]_y}{\sigma_y}, \frac{\sigma_x}{\sigma_y}\right)$$

$$\vec{p}_{i+1} := \vec{p}_i - \vec{k}\left(\frac{q}{2\pi\gamma(\sigma_x + \sigma_y)}\right)s$$

Since the documentation of `bbi_kick` assumes some prior knowledge, there is a physicality argument included in Subsection 5.1 of the appendix. It explains why the momentum is subtracted above instead of added.

2.2 Moving Cloud

In order to calculate the expected position change of the cloud, the whole gaussian carries with it an accumulated momentum $\vec{p} = (p_x, p_y)$. If the particle is determined to be part of a new bunch, the momentum and position of the electron cloud are reset to 0, then calculations proceed as normal. If, however, the particle is a continuation of the current bunch, then we take the time difference between the previous bunch and the current, multiply that by $\vec{p}$, then divide by the total mass of the cloud (given by $m_c = \frac{qm_e}{e^-}$). This gives the first order approximation for the change in position for the cloud[1]. After the particle kick has been calculated, the same kick times the reference energy of the particle (in order to get absolute momentum change instead of angular) is subtracted from the total momentum of the cloud, though it is also multiplied by the relative charge of the macro-particle versus the charge of an ordinary positron to account for the assumptions made in `bbi_kick`. This new $\vec{p}$ is saved for the next particle interaction.

For a particle with given (x, y, p_0) in a lattice element with length (s) we update the cloud characteristics $(\vec{\mu}_i, \vec{p}_i, \vec{\sigma})$ as follows:

$$\vec{\mu}_{i+1} := \vec{\mu}_i + \vec{p}_i\left(\frac{e^-}{qm_e}\right)c\Delta t$$

$$\vec{k} = \text{bbi\_kick}\left(\frac{x - [\vec{\mu}_i]_x}{\sigma_x}, \frac{y - [\vec{\mu}_i]_y}{\sigma_y}, \frac{\sigma_x}{\sigma_y}\right)$$

$$\Delta\vec{p} = \vec{k}\left(\frac{q}{2\pi\gamma(\sigma_x + \sigma_y)}\right)$$

$$\vec{p}_{i+1} := \vec{p}_i + \Delta\vec{p}\left(\frac{q_{macro}}{e^-}\right)p_0$$

Notice the length of the chamber is not added to the momentum of the cloud, this would only be removed again when calculating the displacement (by dividing momentum by total mass of electrons).

2.3 Cloud Pinching

Cloud pinching changes the effective charge of the cloud during the passage of a bunch. It uses the z position of the particle (which is relative to the center of the particle bunch) to scale the charge q' of the cloud between q and $(\alpha + 1)q$ for some parameter α. It approximates this growth using a gaussian centered about the end of the bunch ($z = \sigma_z$):

$$q' := q\left(1 + \alpha e^{-\left(\frac{z}{\sigma_z}+1\right)^2}\right)$$

This new q' is then substituted into any of the previous equation where q would be used.

This increase in the effective density is to match the increase seen in ecloud simulations[2]. See Figure 14 for pinching model example.

[1] Could instead implement a runge-kutta style approximation, but difficult due to execution order of particles.

[2] `https://wiki.classe.cornell.edu/pub/ILC/Private/CesrTA/CollabMeetings/EC_WB_STP_20151201.pdf`

2.4 Feedback

The executable employed (`multibunch`) will reset the x and y position and momentum at the end of each turn. The center of mass on each dimension may be calculated (assuming all particles are weighted proportionally to their charge), and then subtracted from each respective dimension. The amount that is subtracted is scaled by the strength of the feedback (0 is no feedback, 1 is full reset). This setting is contained in the `beam_def.in` file

2.5 Centering

To simulate the passage of a train of bunches, cloud centering may be enabled. This setting will instruct the cloud to be generated at the centroid position of the bunch as opposed to the center of the chamber. This is meant to simulate the displacement caused by preceding bunches. This effect places the cloud-beam system into a minimum potential energy well, thus theoretically causing the cloud to oscillate as the beam passes through. In practice the beam is often close enough to the origin that such a displacement makes no effective difference.

3 Results

3.1 Tune Shifts

The presence of the electron cloud by itself causes a tune shift in both the vertical and horizontal direction. See Figure 3 and Figure 4. The points are too noisy to determine whether the static and dynamic clouds differ.
The motion of the cloud can be seen in Figure 2.

3.2 Bunch Growth

The bunch passing through the cloud will generate emittance growth dependent on the density of the cloud. The densities are based on the slides from Jim Crittenden indicating the density in the chamber near the cloud is on the order of 10^{12} $e^{-}.m^{-3}$.
Plotted in Figure 5 is the bunch growth on the vertical axis of the beam as it passes through a moving cloud with no pinch. Both the static and the dynamic cloud models appear to increase the bunch size.
Turn by turn size measurements can be seen in Figure 6 and Figure 7.
Bunch size plotted is based on the average size for the last 500 turns.

3.3 Varying Initial Offset

[Not yet updated to newest lattice]
By varying the initial offset of the bunch we can cause the vertical size to increase. See Figure 8. This initial bunch growth dampens with time, but remains clearly visible even after 50,000 turns.

3.4 Head-Tail Motion

By taking the difference between the xz and yz slopes from the cloud influenced bunches and the control bunch we can determine to what extent the presence of a static or dynamic cloud may cause head-tail motion. See Figure **??** and Figure **??**.

The two largest peaks to the right of 0.5 are around 0.510 and 0.637 for XZ, and around 0.528 and 0.672 for YZ.

3.5 Varying Pinching

[Not yet updated to newest lattice] Varying the pinching coefficient yielded no conclusive data due to the large size variations of the bunch size. As such, while the pinching increased the amplitude of the variations and apparent instability, the actual average size did not increase much (except for two notable occasions) see Figure 13 for results, and Figure 14 for pinching model.

3.6 Comparison to Experiment

For experimental results I will refer to the December shifts[3].
First note is that the cloud charges described in this document cannot be cleanly converted to electron density because this model only includes the electrons immediately adjacent to the beam. This omits the gaussians on either side of the chamber.
Before proceeding with any more comparisons to experimental data I will consult on the results thus far and ask what methods may prove most effective for determining whether this is a valid model.

4 Simulation conditions

This simulations have all been performed using the `cta_2085mev_xr20m_20151208.lat` lattice. Radiation damping is enabled. Predefined initial emittance values of $a = 3.0e{-}9$, $b = 2.0e{-}9$, with length $\sigma_z = 1.0e{-}2$. The bunch contained a charge of $10^{-8}C$ (default value). The cloud parameters unless otherwise noted are $\sigma_x = 1e - 5m$ and $\sigma_y = 3e - 5m$

[3] `https://cesrwww.lepp.cornell.edu/logs/CTA+MS/2270` and `https://cesrwww.lepp.cornell.edu/logs/CTA+MS/2276`

5 Appendix

5.1 Beam Beam Interaction Physics

Consider the following plot of the behavior of the `bbi_kick` function:

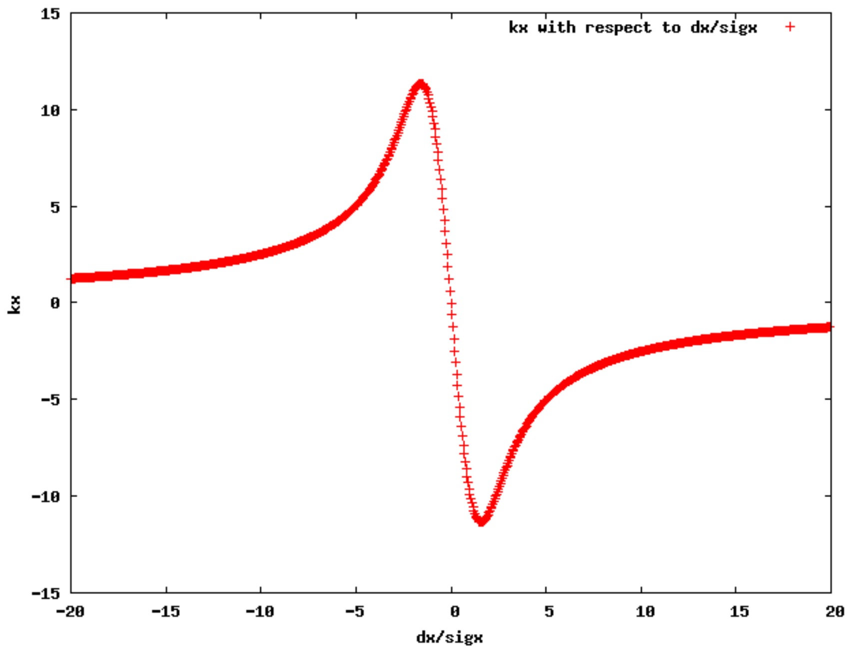

Figure 1: bbi_kick output

Therefore k_x is, conceptually, a kick for the particle towards the cloud (meaning when the particle x position is less than that of the cloud, the k_x is positive, when the x position is great, the k_x is negative). This means that `bbi_kick` assumes the particle and the cloud are of opposite charge.

`bbi_const` is equal to $\left(\frac{q}{2\pi\gamma(\sigma_x+\sigma_y)}\right)$. Where q is the total charge of the cloud. Since the cloud is composed of electrons, $q < 0$ and bbi_const < 0. Thus when it is multiplied by $\vec{k}$ we instead get $\vec{k}$ as the kick on the particle if it had the same signed charge as the cloud. To compensate we will subtract this kick from the particle, and add it to the cloud.

5.2 Example `snapshot/cloud_settings.in`

```
&cloud_settings
  cloud_active= T
  cloud_motion= T
  cloud_centered= F
  cloud_start= 4.5e-14
  cloud_growth= F
  cloud_pinch= F
  cloud_pf= 0
  cloud_start_sxx= 0.0001
  cloud_start_syy= 0.001
/
```

6 Plots

Appendix section for plots. Units are in μm and unitless number of turns unless marked otherwise. For cloud characteristics there are two possible units of measurement, p and q. p is the electron density near the beam area, generally on the order of $10^{12}e^{-}.m^{-3}$, whereas q is the total charge of the cloud, generally on the order of $10^{-14}C$. The conversion is approximate due to the gaussian shape of the cloud.

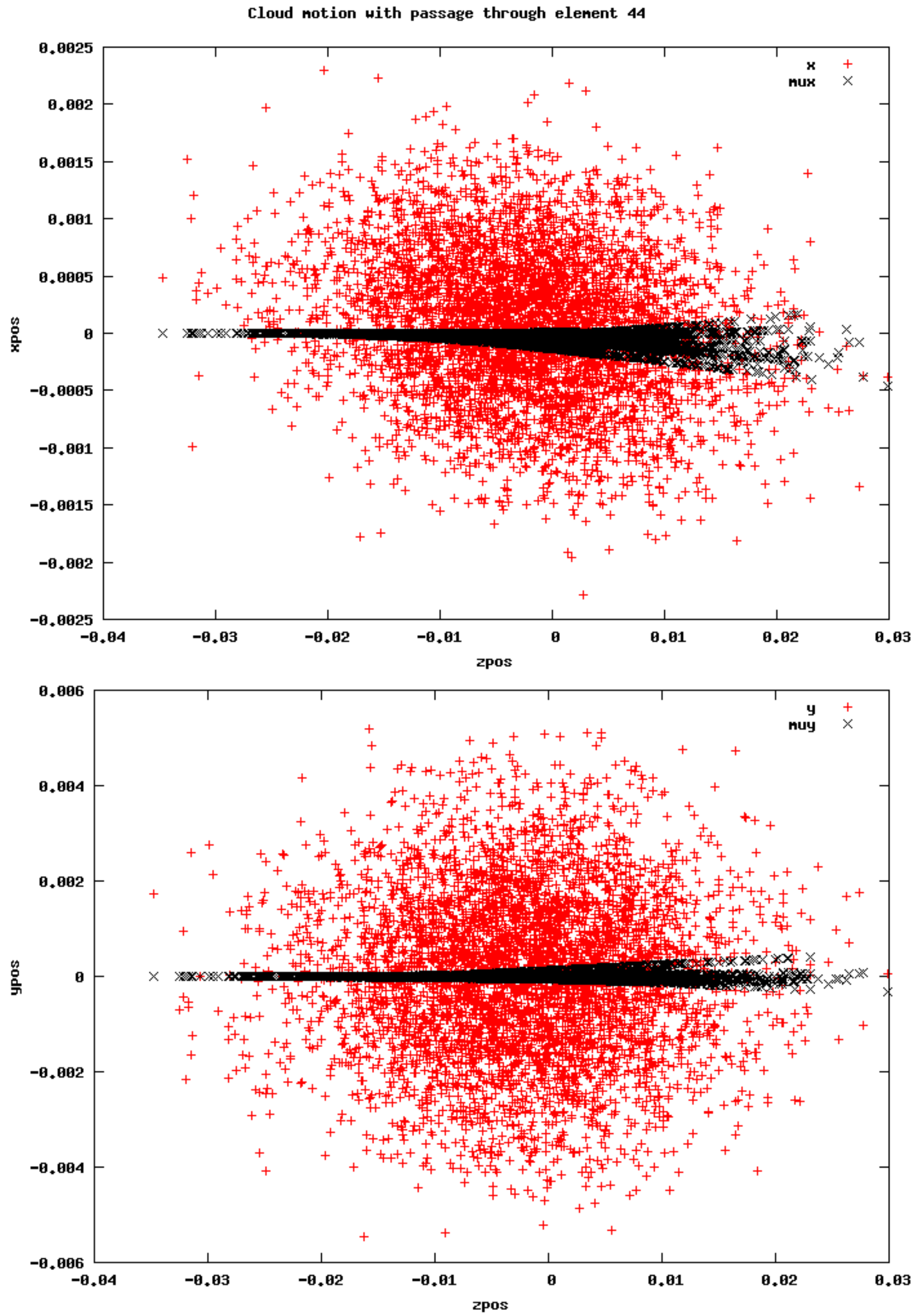

Figure 2: Cloud motion through first sbend

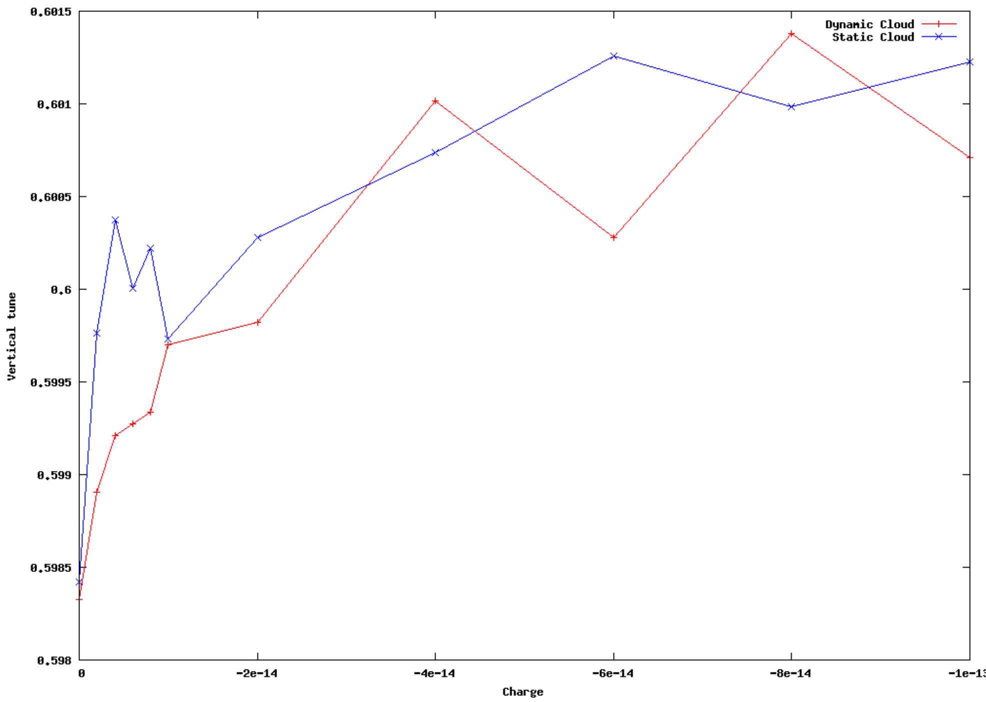

Figure 3: Vertical tune from dynamic cloud

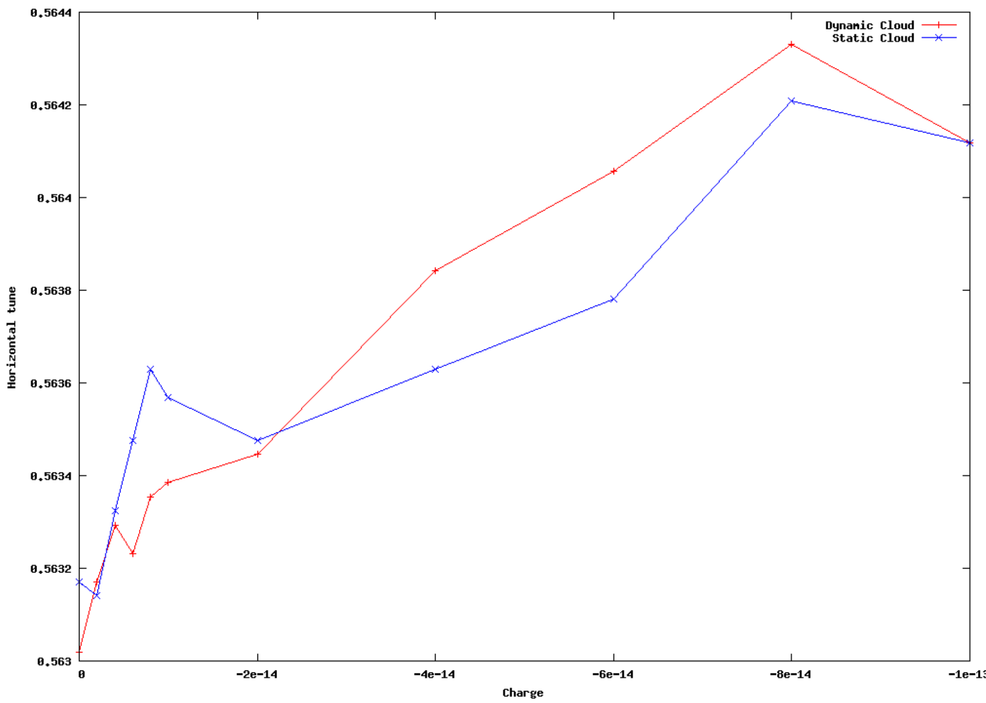

Figure 4: Horizontal tune from dynamic cloud

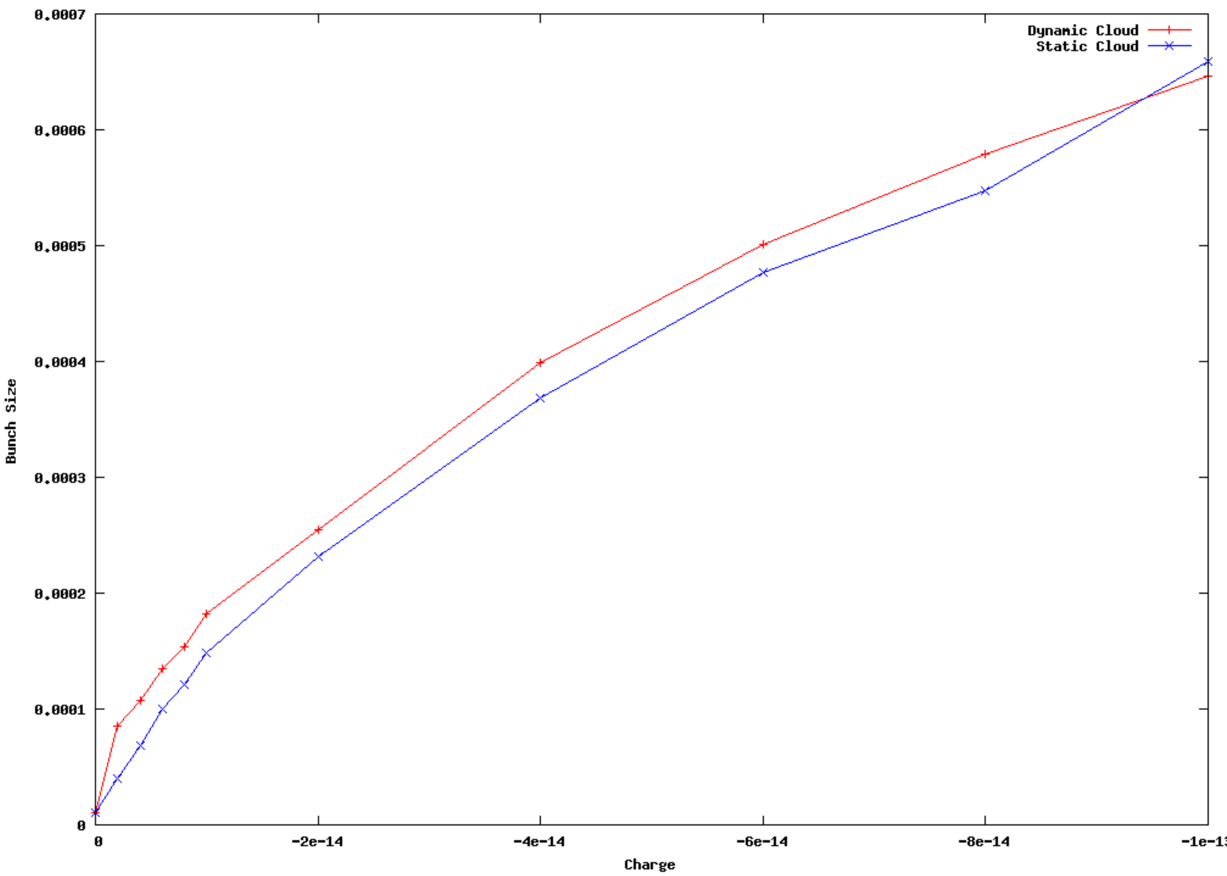

Figure 5: Bunch size growth from dynamic cloud

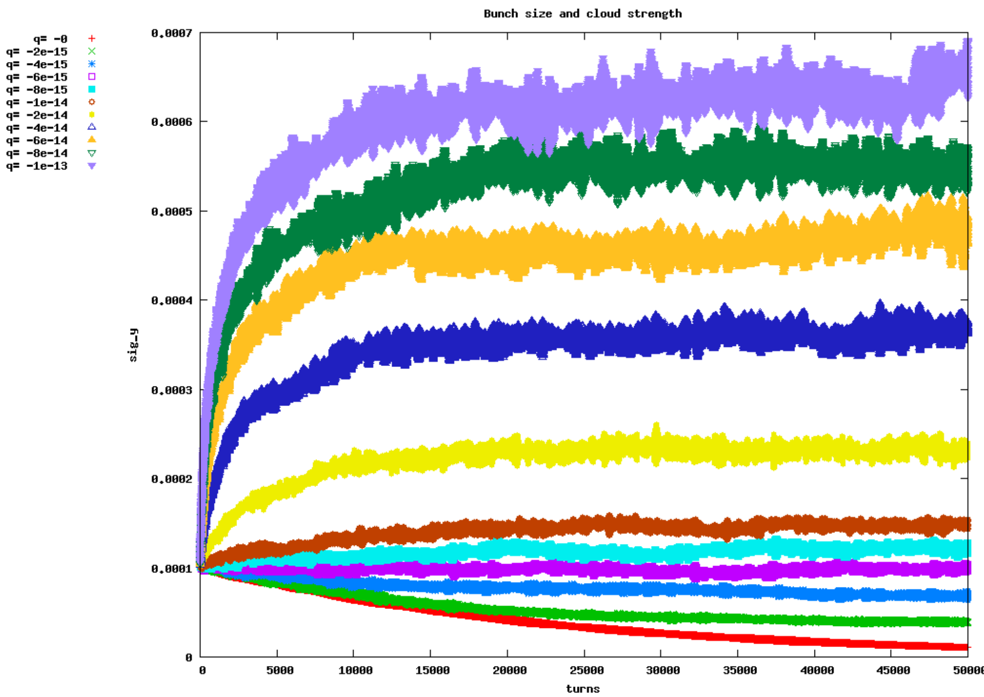

Figure 6: Vertical bunch size for static cloud

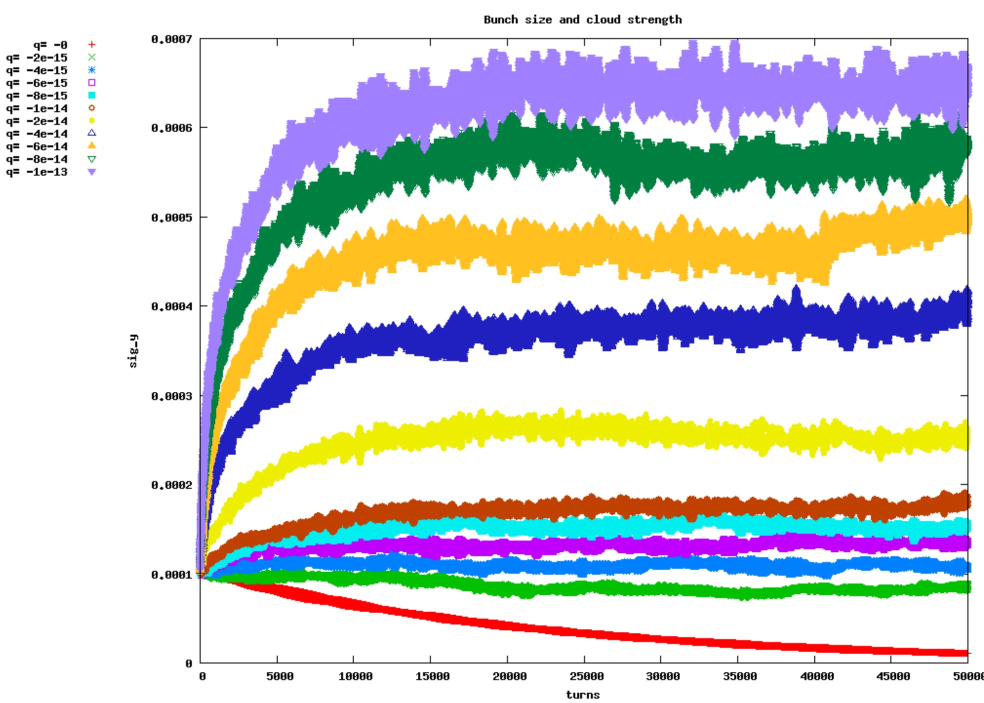

Figure 7: Vertical bunch size for dynamic cloud

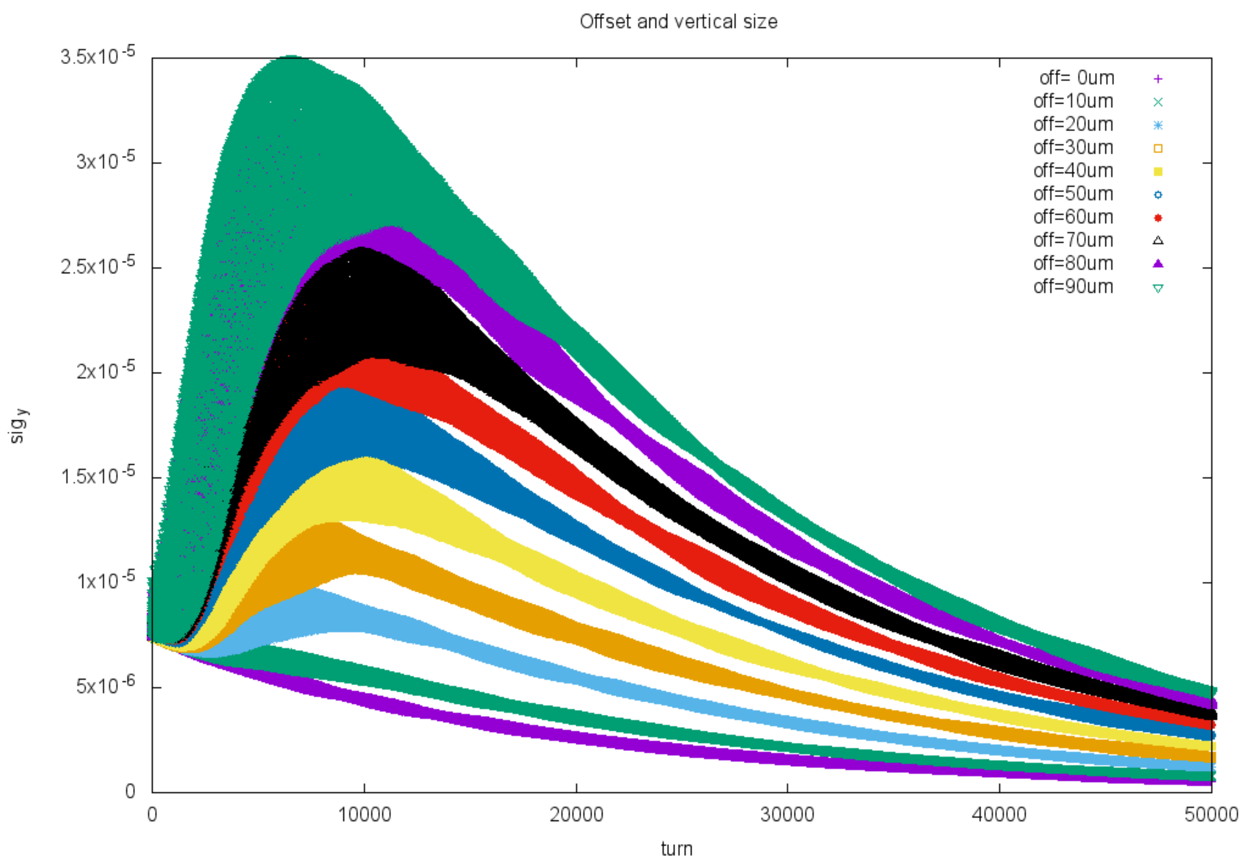

Figure 8: Vertical size for varying initial offsets

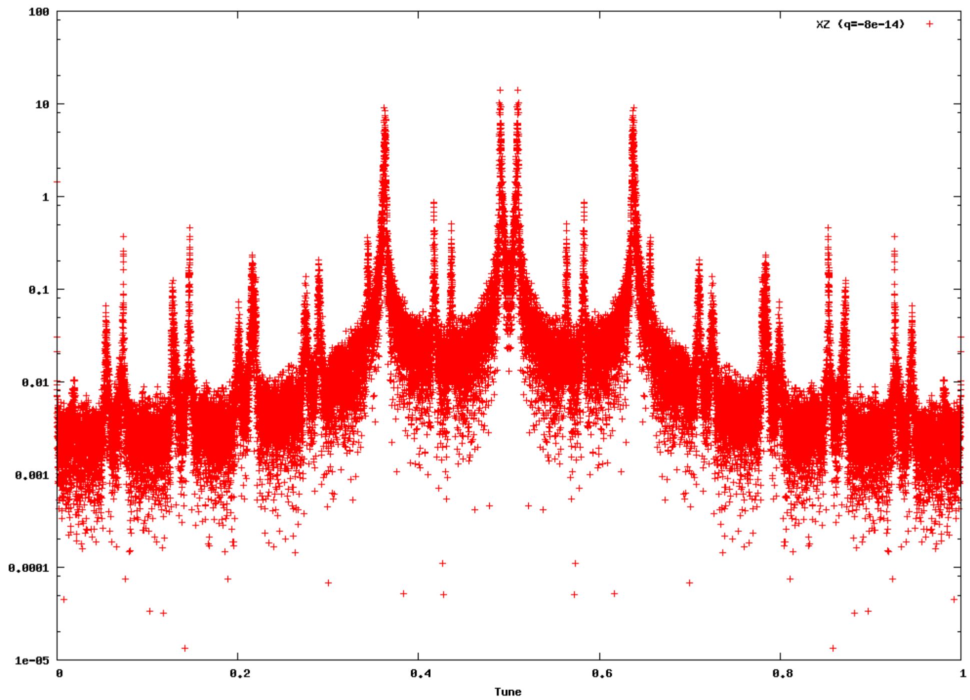

Figure 9: Head-tail motion frequency on xz plane

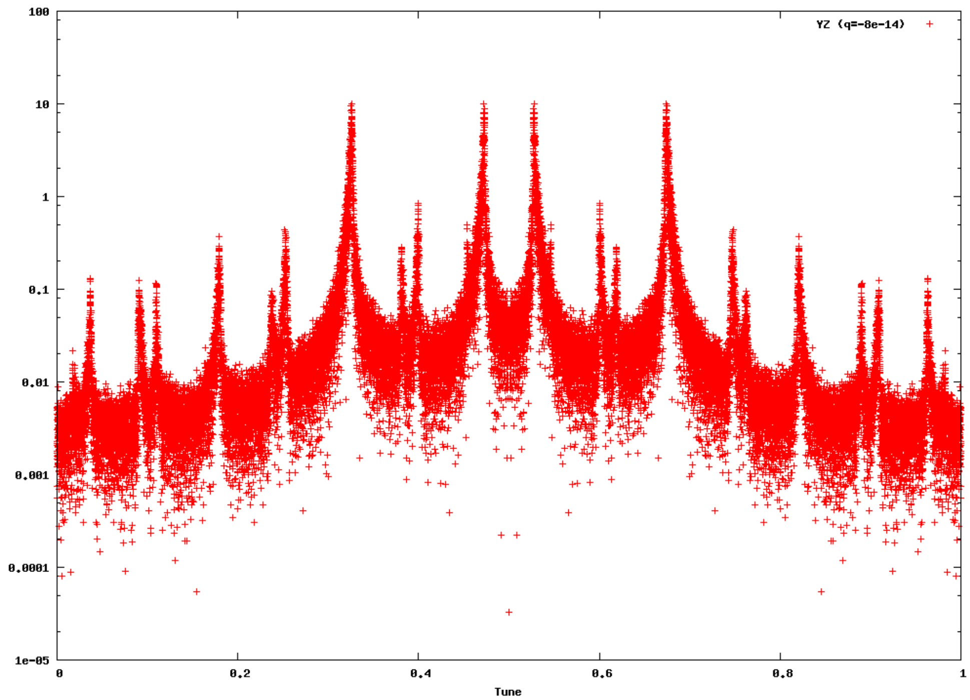

Figure 10: Head-tail motion frequency on yz plane

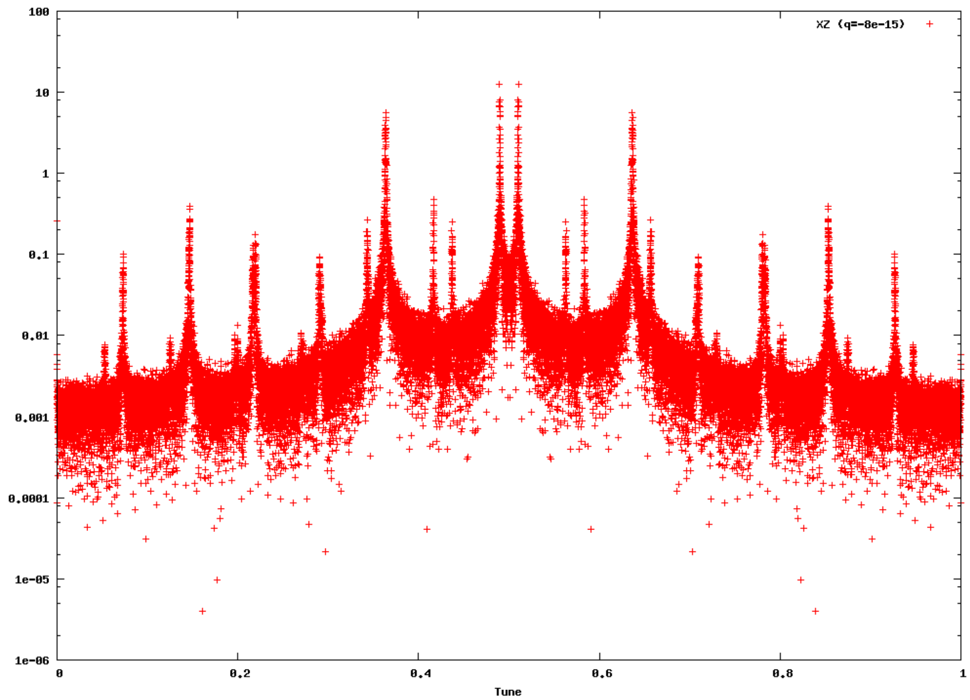

Figure 11: Head-tail motion frequency on xz plane

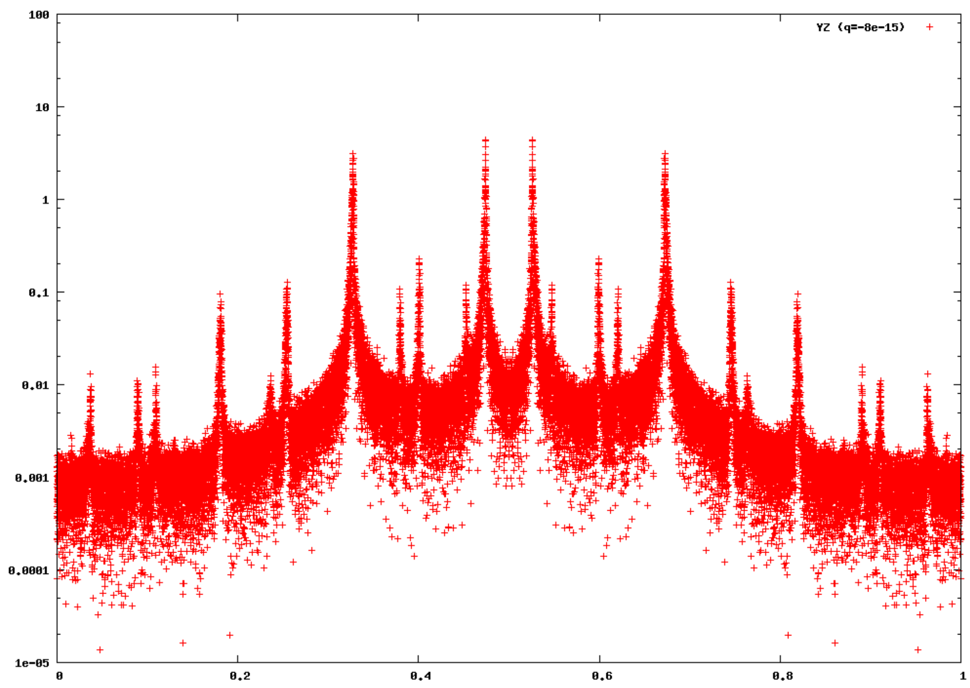

Figure 12: Head-tail motion frequency on yz plane

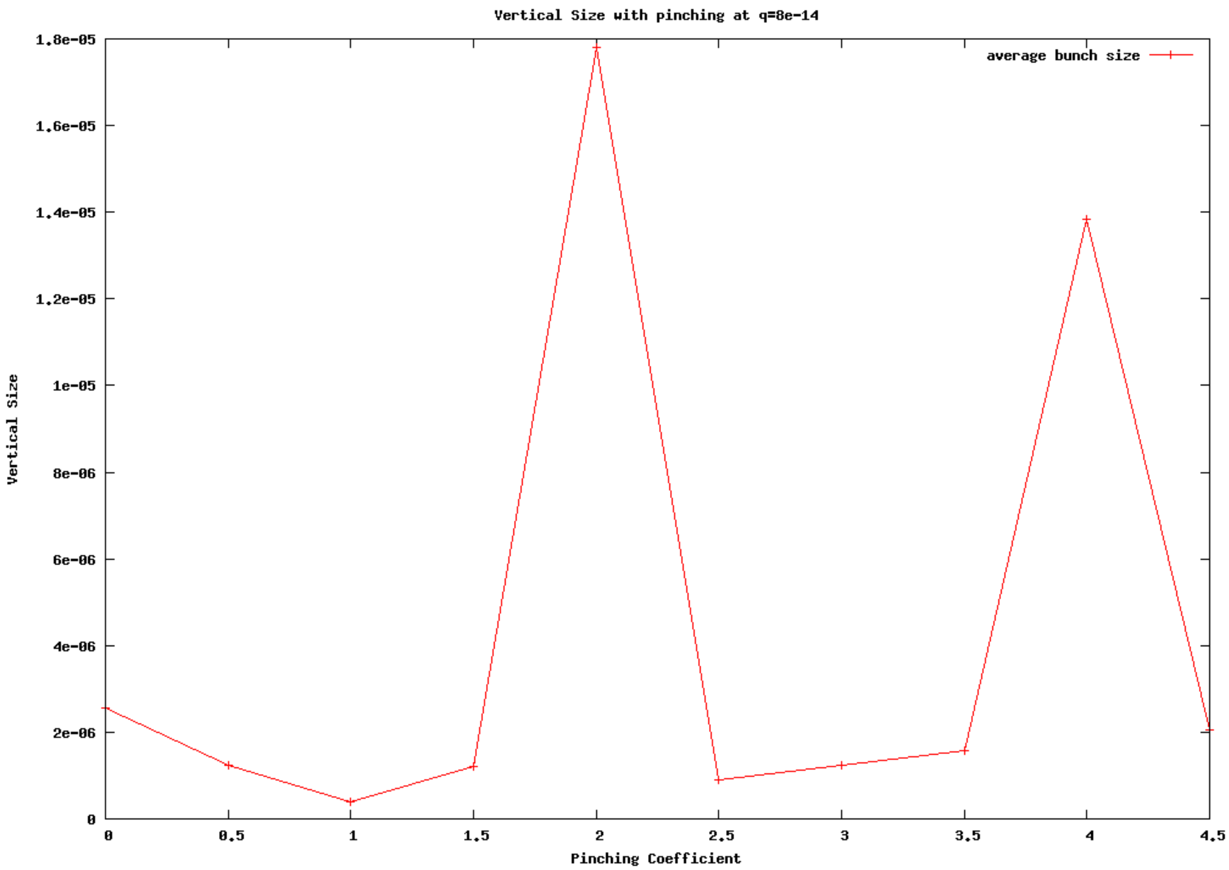

Figure 13: Vertical size for varying pinching coefficients [out of date]

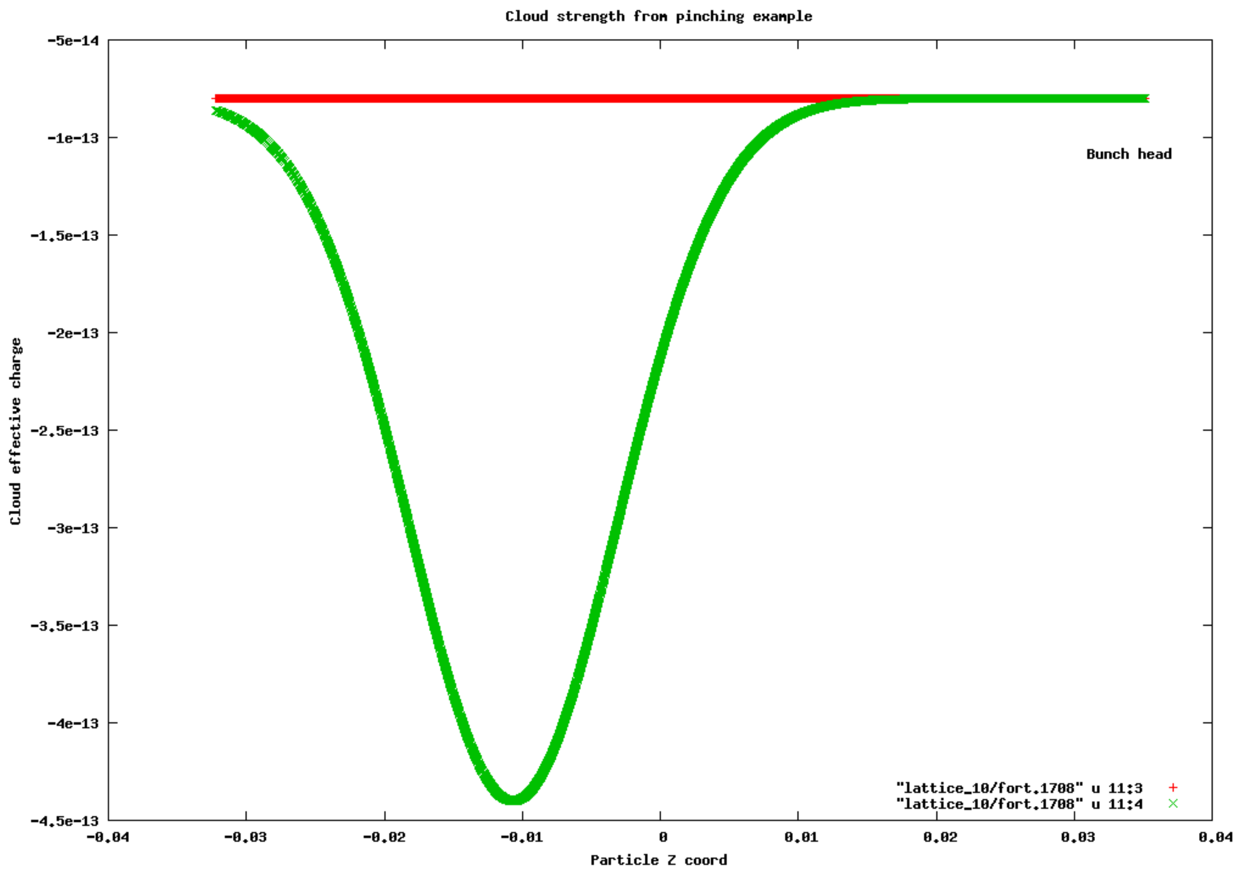

Figure 14: Model for pinching effect

7 Citations

Jim Crittenden's Sept 30th slides:
https://wiki.classe.cornell.edu/pub/ILC/Private/CesrTA/IBSmeet/crittenden_30sep15.pdf