SINGLE-BUNCH ELECTRON CLOUD EFFECTS IN THE GLC/NLC, US-COLD AND TESLA LOW EMITTANCE TRANSPORT LINES*

D. Chen, A. Chang, D. Bates, M.T. F. Pivi#, T. O. Raubenheimer
SLAC, Menlo Park 94025, California, USA

Abstract

This paper examines the severity of the electron cloud effects in the Low Emittance Transport (LET) of linear colliders including the Bunch-Compressor System (BCS) and Beam Delivery System (BDS). We examine the electron cloud effects in the normal-conducting GLC/NLC or X-Band, and the super-conducting US-Cold and TESLA linear collider designs through the use of specially developed computer simulation codes. An estimate of the critical cloud density is given for the BDS and BCS of the X-Band collider.

INTRODUCTION

The electron-cloud effect (ECE) has been observed or is expected at many storage rings [1]. In the beam pipe of the Beam Delivery System (BDS) and Bunch-Compressor System (BCS) of a linear collider, photoelectron production, ionization of residual gasses and secondary emission may lead to electron-cloud during the bunch train passage. A positron bunch passing through electron cloud may experience additional focusing or the cloud may cause a collective instability. These effects may be significant in the BDS where the beta functions are very large even though the beam energy is high and in the BCS where the beam energy is quite low.

MODEL AND CODES DESCRIPTION

We have used the simulation code CLOUD_MAD [2] developed to study the electron cloud effect in the transport lines of linear accelerators. The application CLOUD_MAD tracks a beam through a magnet lattice, input in the form of a MAD deck. The electron cloud is represented as a distribution of macro-particles and the beam-cloud interaction is calculated in the middle of every element in the MAD deck. The field of the electron cloud is calculated in the two transverse degrees of freedom using an FFT method. The cloud boundary radius is typically set to 1 ~ 0.5 mm and corresponds to the distance beyond which electrons would not be noticeably affected by the passing positron bunches. This study has assumed an initial electron cloud that does not depend on location along the transport beam line. Because of the different chamber geometry, the different levels of synchrotron radiation, and the different magnetic fields, different electron cloud densities will exist at different parts of the beam line. This should be included in future studies. Furthermore, this study assumed a single bunch and an initial electron cloud that is uniform. The generation and development of the electron cloud in the LET systems is predicted by the code POSINST [1,3] and simulation results are presented in the last section of the paper.

LOW EMITTANCE TRANSPORT LINES

Beam Delivery System

If the electron cloud density is allowed to grow to high densities along the bunch train, see the *Generation of the Cloud* section below, various detrimental single-bunch effects may appear in the BDS. In this paper, we study single-bunch effects that impact the spot size at the IP assessed with simulations using CLOUD_MAD. Changes in the beam were indicated by variations in the beam emittances and spot sizes near the IP. Unless otherwise stated, all data are normalized to emittances and spot sizes at 1.0e07 e/m^3, where the electron cloud has no observable effects.

A significant, near-exponential growth in emittances and spot sizes occurs above what we now designate a threshold cloud density ~1.0e11 e/m^3, shown in Fig. 1 [4].

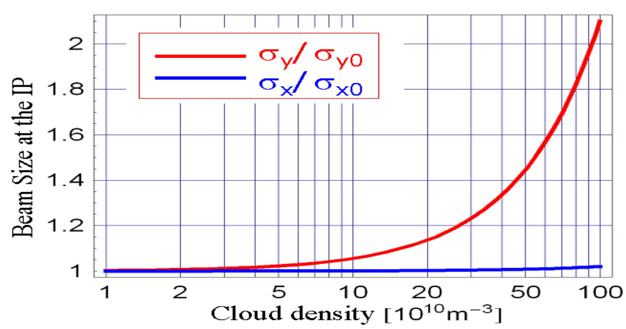

Figure 1. Simulation of beam-size blow-up at the IP as a function of the cloud density in the beam delivery system.

Below this, the beam shows little variation; beyond this, the IP beam size grows rapidly. We estimate the importance of two of the possible effects: first, phase advance changes through the Chromatic Correction Section (CCS) due to focusing from the beam-electron interaction that may impact the compensation of the geometric aberrations and, second, the direct spot size change at the IP due to the additional focusing through the Final Transformer (FT) of the final focus. We study beams with both a correlated and an uncorrelated incoming energy spread in case this has an impact similar to that described in Ref. [5].

To see which was more important, we tracked a beam with zero energy spread through the lattice with the sextupoles on and sextupoles off. In both cases, we observed a similar threshold at an initial electron density

*Work supported by US DOE under contracts DE-AC03-76SF00515.
#mpivi@SLAC.Stanford.EDU

1.0e11 e/m^3, indicating that the breakdown of the chromatic correction section is not the dominant contribution to the increase in the IP spot size. Direct focusing effects appear to be more important. An estimation of the changes to the IP spot size is given [4]:

$$\frac{\Delta\sigma_{x,y}}{\sigma_{x,y}} \approx k_1 \int_0^L \beta_{x,y} ds' \sin^2 \left[\phi(s) - \phi(s')\right] \qquad (2)$$

where $\phi(s)$ is the phase advance, $\beta_{x,y}$ the horizontal and vertical beta functions and L is the length of the beam line. As the electron cloud density increases, the focusing increases and this will change the location of the beam waist at the IP. Since $k_1 \sim n_0 r_e / \gamma$, the beam size growth $\Delta\sigma/\sigma$ is linear with the cloud density n_0. With a 250 GeV beam and an electron density of 1.0e11 e/m^3, the vertical IP spot size $\Delta\sigma/\sigma$ is estimated to be ~30%. If the cloud density were constant along the bunch train, this additional focusing would be straightforward to correct however as discussed in section *Generation of the Cloud*, the cloud density will vary along the 300 ns train and thus any correction would have to be in the form of an rf quadrupole.

Coupled-bunch instabilities have been estimated at a threshold 3.6e12 e/m^3 and will be discussed in separated paper.

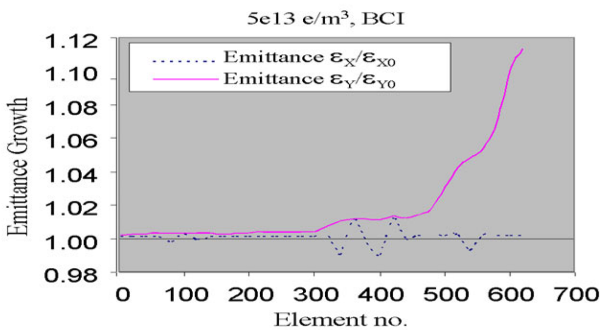

Figure 2. Emittance growth in the 1st section (BCI) of an X-Band BCS for a ~threshold cloud density 5.0e13 e/m^3.

Bunch Compressor System

In leaving the damping ring, a positron bunch is typically 5 mm in length. By the time it reaches the main linac, it needs to be reduced in length to 110 µm. For simulation purposes, the bunch compressor system has been divided into three sections: bunch compressor I (BCI) at 2 GeV, bunch compressor II (BCII) at 8 GeV, and the pre-linac (PLIN) section, which lies between the two bunch compressors. At an electron cloud density 5.0e13 e/m^3, as we proceed along the BCI section, there is a steady rise in the vertical emittance and a stable oscillation in the vertical spot size [6]. The emittance growth peaks at 12% near the end of BCI. The effects in BCII are even more pronounced. The emittance rises as much as 18%. In the Pre-linac, emittance and spot size growths top at 14% and 6% as shown in Figs. 3 and 4. As in the case of the BDS, the effects are a strong function of the electron cloud density. At an electron cloud density 5.0e14 e/m^3, the Pre-Linac vertical spot size increases by an order of magnitude, Fig.5.

We can estimate the betatron mismatch over a cell [6] as

$$\frac{\Delta\beta}{\beta} \approx L_{cell}\overline{\beta}(s)k_1(s) = L_{cell}\overline{\beta}(s)n_e H_e \frac{4\pi}{\gamma} r_e \qquad (3)$$

where L_{cell} is a matching length, $\beta(s)$ is the beta function, k_1 = 3x10^{-4} m^{-2}, n_e is the neutralization density of 5.0e13 e/m^3 for a 10 mm round vacuum chamber, H_e is an enhancement specific to the section, and we have assumed a flat beam and flat distribution for the trapped electrons in the positron beam. For a typical cell in the pre-linac this yields $\Delta\beta/\beta$ ~ 0.03 which is not inconsistent with the observed beam size oscillations in Fig. 4.

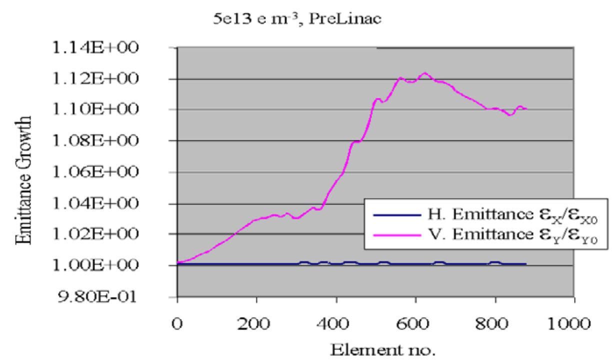

Figure 3. Emittance growth in the Prelinac section of an X-Band BCS for a ~threshold cloud density 5.0e13 e/m^3.

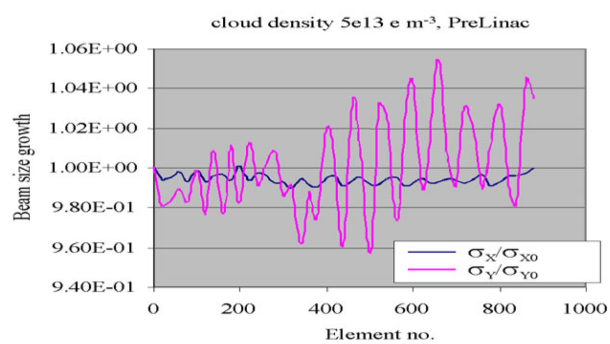

Figure 4. Beam size in the Prelinac section of an X-Band BCS for a ~threshold cloud density 5e13 e/m^3.

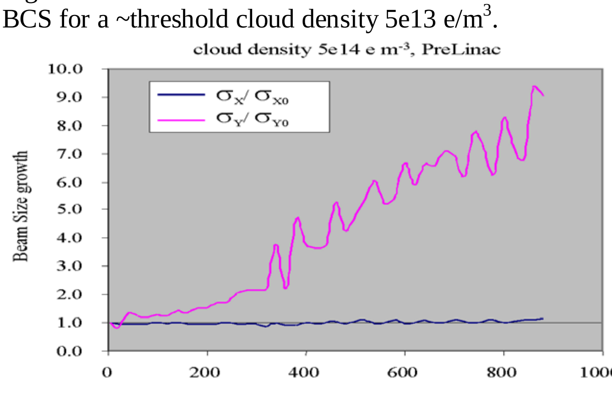

Figure 5. Beam size growth in the Prelinac section of an X-Band BCS for an above threshold cloud density 5e14 e/m^3.

GENERATION OF THE CLOUD

In the positron transport lines, electron cloud generation is only expected to be an issue for the normal conducting colliders where the bunches are closely spaced, and not for USCold or TESLA where the bunch spacing is 337 ns. Electron-cloud in various elements of the USCold linear collider is shown in Fig. 6.

In the X-Band collider design, the bunch train is roughly 268 ns in length. Depending on the vacuum chamber radius, material and conditioning, an electron cloud can be generated which will approach the neutralization density. For example, with a 10 mm radius chamber and a secondary electron yield (SEY) of 2, the electron cloud reaches a density of roughly 1.0e14 e/m^3 by the end of a positron bunch train, as shown in Fig. 7.

In the X-Band collider transport lines, the electron cloud density just after the passage of a 268 ns bunch train is a strong function of the vacuum chamber radius as well as the SEY, as shown in Fig. 7. By decreasing the SEY to 1.5 or increasing slightly the vacuum chamber radius, as shown in Fig. 8, the peak cloud density can be reduced to acceptably low values. However, the effects of photoelectrons must still be taken into account in both normal- and super-conducting linear colliders.

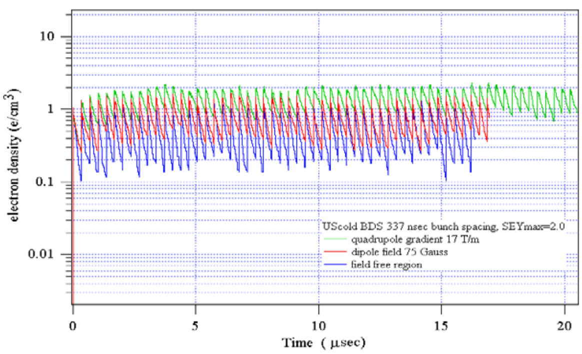

Figure 6. Simulated electron cloud density, in units e/cm^3, in the USCold BDS, from ionization of residual gasses. Assumed a peak secondary electron yield of 2.0.

CONCLUSIONS

Electron cloud effects can severely disrupt the normal passage of a positron beam through the beam delivery system BDS of a normal conducting linear collider. The threshold for the beam size blow-up at the IP is at an electron cloud density in the BDS of ~1.0e11 e/m^3. These studies have been performed assuming a 250 GeV beam and the effects will at least scale as 1/sqrt(γ) and most likely 1/γ. The problem of avoiding beam-electron instability is highlighted in all three subdivisions of the bunch compressor system BCS. Large emittance growths and spot sizes always appear at densities above 5e13 e/m^3 due to a combination of collective effects and the betatron mismatch due to the increased focusing from the cloud. The existence of the threshold density suggests one solution: reducing cloud density to lower levels to minimize beam blow-up. In the positron transport lines, the electron cloud generation is only expected to be an issue for the normal conducting colliders where the bunches are closely spaced. By decreasing the SEY to 1.5 or increasing slightly the vacuum chamber radius, the peak cloud density can be reduced to acceptably low values.

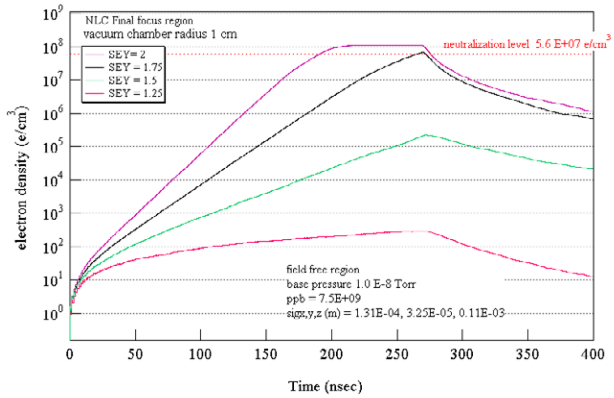

Figure 7. Simulated electron cloud build-up by residual gas ionization, in units e/cm^3, in the X-Band BDS for different SEY, during the pass of a bunch train.

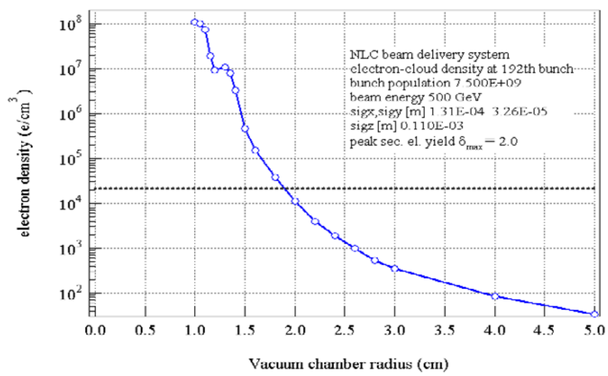

Figure 8. Cloud density just after the pass of a bunch train (see Fig. 7), in units e/cm^3, with vacuum chamber radius, in the X-Band BDS. The source is residual gas ionization.

REFERENCES

[1] Electron cloud updates at the ICFA Workshop ECLOUD04, Napa, CA, US, April, 2004: http://icfa-ecloud04.web.cern.ch/icfa-ecloud04/.

[2] CLOUD_MAD, T. O. Raubenheimer; reference page http://wwwproject.slac.stanford.edu/lc/local/AccelPhysics/Codes/Ion_MADCloud_Mad/dbates/nlc_cloudmadtools_doc/cloud_mad/index.html

[3] M. A. Furman, G. R. Lambertson LBNL-41123/CBP Note-246, PEP-II AP Note AP 97.27, 1997.

[4] D. Chen, A. Chang, D. Bates, M.T.F. Pivi and T.O. Raubenheimer, "Single Bunch Electron Cloud Effects in the NLC Beam Delivery System," SLAC-TN-03-051 and NLC LCC-0126, 2003.

[5] P. Emma, T.O. Raubenheimer, F. Zimmermann, "Emittance dilution by ions in the SLC arcs," Proc. EPAC 1994, p. 1162.

[6] D. Chen, A. Chang, D. Bates, M.T.F. Pivi, and T.O. Raubenheimer, "Single Bunch Electron Cloud Effects in the NLC Bunch Compressor System," SLAC NLC LCC-0131, 2003.