Anti-Crab cavities for the removal of spurious vertical bunch rotations caused by crab cavities

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Many particle accelerators are proposing the use of crab cavities to correct for accelerator crossing angles or for the production of short bunches in light sources. These cavities produce a rotation to the bunch in a well defined polarisation plane. If the plane of the rotation doesn't align with the horizontal axis of the accelerator, the bunch will receive a small amount of spurious vertical bunch rotation. For accelerators with small vertical beam sizes this can cause significant unwanted effects. In this paper we propose the use of a 2nd smaller crab cavity in the vertical plane in order to cancel this effect.

PACs numbers: 29.20.Ej, 41.75.Ht, 41.85.-p

I. INTRODUCTION

Particle colliders often employ a finite crossing angle between colliding bunches. The associated loss of luminosity for long thin bunches can be recovered by rotating the bunches prior to collision, such that the bunches will now have an effective head-on collision. One method of rotating the bunches is to use a crab cavity [1]. Theses devices are deflecting mode cavities in which the cavity phase is set such that the head and tail of the bunch receive equal and opposite kicks, and the centre of mass receives zero kick. This will impart a transverse momentum to the bunch which causes the bunch to rotate as it travels along the beam-line. Crab cavities are required for several particle colliders such as KEK-B [2], the International Linear Collider (ILC) [3], the LHC upgrade [4] and CLIC [5] and also a number of light sources such as the Argonne light source, ALS [6].

Crab cavities typically operate using the TM_{110} mode of an RF cavity, in which the transverse electric and magnetic fields act together to kick the bunches in the same plane. This mode has a well defined polarisation in which it provides the kick. However if the polarisation of the operating mode of these crab cavities are not perfectly aligned with the horizontal axis of the accelerator, then a small amount of the crabbing effect will take place in the beams' vertical plane. This will cause the bunches to collide with a small vertical crossing angle. If the bunch has a smaller vertical beam size than horizontal beam size this could cause a large luminosity reduction as is the case in the ILC and CLIC. Such a vertical rotation has been observed during operation at KEK-B [2]. There are also a number of other sources of vertical crabbing due to x-y coupling. There are a number of approaches to correct for this vertical rotation, such as active mechanical tuners to rotate the cavity in-situ, beam tuning knobs or using correction cavities. In this paper we propose the use of vertical crab cavities, referred to as anti-crab cavities, to counter-act this effect. In such a scheme a smaller (single-cell) crab cavity is placed close to the crab cavity, with its operating polarisation in the vertical plane. The anti-crab cavities fields would be in-phase with the crab cavity fields such that the centre of mass does not receive a transverse kick in either plane. The anti-crab cavity would them provide additional vertical momentum to the bunch such that the head and tail of the bunch receive equal and opposite kicks. The amplitude in the vertical can then be adjusted until the anti-crab cavity cancels any vertical momentum imparted to the bunch by the crab cavity. This can be achieved in a linear collider by measuring the luminosity while varying the cavity amplitude.

In this paper we look at the theory of such a device and numerically model an anti-crab cavity for use in the ILC. We then simulate the use of this anti-crab cavity in the beam delivery system of the ILC, using the particle tracking code PLACET [7] together with the beam-beam code GUINEA-PIG [8].

II. THEORY

Using a simple geometric argument [9], which neglects beam-beam effects, for beams of bunches intersecting in a horizontal plane at a small angle θ_c, one predicts that the luminosity is reduced with respect to a head on collision by a factor S given as

$$S = \frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_z}\right)^2}} \tag{1}$$

where σ_z and σ_x are the longitudinal and horizontal Gaussian beam sizes and θ_c is the angle between the two colliding bunches.

In this section we assume that a crab cavity is used to eliminate this luminosity reduction and concern ourselves about additional luminosity loss when its alignment is imperfect. .A crab-cavity has a time varying transverse electric and magnetic field such that particle traversing the cavity will experience a transverse kick given as

$$V_{\perp} = V_0 \sin\left(\omega \, s/c\right) \quad (2)$$

where s is the position along the bunch and the centre of the bunch is given at s=0. V_0 is the peak transverse voltage and $V_{\perp}$ is the transverse voltage experienced by the particles. The direction of $V_{\perp}$ is assumed not to be perfectly in the horizontal plane and will have component V_x and V_y. The phase of the crab cavity is adjusted so that the head and tail experience equal and opposite forces whilst traversing the cavity. The effect of the cavity is to start the bunch rotating about its centre.

The transverse offset of any particle in the bunch at the IP, Δx and Δy, is given by

$$\begin{aligned} \Delta x &= R_{12} \frac{V_x}{E} \\ \Delta y &= R_{34} \frac{V_y}{E} \end{aligned} \quad (3)$$

where R_{12} and R_{34} are the transfer matrix elements which relate the angular direction of the particle at the cavity to the offset of the particle at the IP, [10]. Hence substituting (2) into (3), the offset as a function of position is given as

$$\Delta x(s) = R_{12} \frac{V_{0x} \sin\left(\omega \, s/c\right)}{E} \quad (4)$$

by consideration of a particle at the front of the bunch at position $s = \sigma_z$ one determine bunch rotation as

$$\theta_{crab} = \frac{\Delta x(\sigma_z)}{\sigma_z} \approx \frac{\omega}{c} R_{12} \frac{V_{0x}}{E} \quad (5)$$

where the required rotation is $\theta_{crab} = \theta_c/2$. Several factors reduce the amount of luminosity recovered using crab cavities. Phase or amplitude variations can cause a spurious centre of mass kick or change the angle of rotation, respectively [11]. Wakefields induced by the charged bunch in the cavity can impart a transverse kick to following bunches [12]. In addition if the cavity kick has a small miss alignment angle ϕ from the horizontal plane then the desired horizontal crabbing rotation will be given by

$$\theta_{crab} = \frac{\omega}{c} R_{12} \frac{V_0}{E} \cos(\phi) \quad (6)$$

and an unwanted vertical rotation will be given by

$$\begin{aligned} \theta_{vertical} &= \frac{\omega}{c} R_{34} \frac{V_0}{E} \sin(\phi) \\ &= \theta_{crab} \frac{R_{34}}{R_{12}} \frac{\sin(\phi)}{\cos(\phi)} \end{aligned} \quad (7)$$

In this situation, whilst the luminosity loss from horizontal rotation is still eliminated to first order there is an additional luminosity loss from the vertical rotation determined from (1) as

$$S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z \theta_{vertical}}{2\sigma_y}\right)^2}} \quad (8)$$

If the misalignment is small then, by inserting (7) into (8), the luminosity loss is determined from

$$S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z \theta_{crab} R_{34} \sin(\phi)}{2\sigma_y R_{12}}\right)^2}} \quad (9)$$

If the vertical beam size is much smaller than the bunch length this can lead to a significant loss in luminosity. For example as we will see in the next section the ILC has beam parameters such that the cavity would require to be aligned to better than 7 mrad to keep the luminosity loss below 2%. This is a tighter tolerance that is achievable when mounting the cavity hence some active method must be employed to rotate the cavities polarisation. This can be achieved through physically rotating the cavity via a roll tuner, beam based feedback or to use a second cavity. In this paper we will consider the use of a second cavity to rotate the crabbing polarisation. If a second crab cavity is placed in the beam-line with a vertical crabbing effect, rather than a horizontal one, this can be used to provide an opposing kick, cancelling the spurious rotation. Such a cavity would require a voltage of

$$V_{anticrab} = V_{crab} \varphi_{max} \quad (10)$$

which would allow a single cell anti-crab cavity to compensate for the roll misalignments of several crab cavities.

Such a cavity would be susceptible to a tight phase requirement as in the regular crab cavity. The offset at the IP due to a phase error is given by

$$\Delta y_{ip} = R_{34} \frac{V_y}{E_o} \sin(\Delta\varphi) \approx R_{34} \frac{V_y}{E_o} \Delta\varphi \quad (11)$$

If we assume that we can tolerate a vertical deflection of $\sigma_y/4$ then the phase tolerance is

$$\Delta\varphi \approx \frac{E_o \Delta y_{ip}}{R_{34} V_y} \quad (12)$$

this places a limit on the maximum operating voltage of the anti-crab cavity in order to avoid excessive luminosity reduction due to phase errors.

III. ANTI-CRAB CAVITY OPERATION IN THE ILC

The ILC has a crab crossing of 14 mrad and collides electron and positron beams at 500 GeV CoM. The ILC beam delivery system includes two 9 cell superconducting crab cavities. These cavities operate at a frequency of 3.9 GHz and a maximum gradient of 5 MV/m. The cavity, shown in Fig 1, has a cell length of 38.4 mm, an iris radius of 15 mm in the mid cells and 18 mm in the end cells and an equator radius of 47.18 mm.

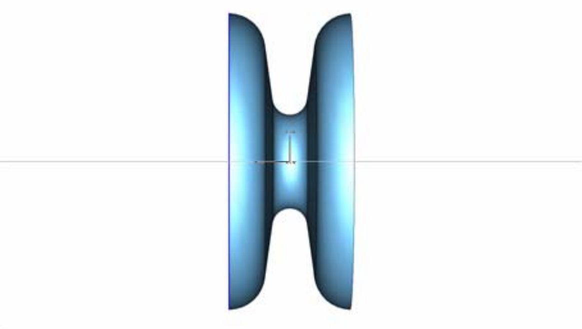

FIG. 1. The ILC crab cavity mid-cell shape.

In the ILC Beam Delivery System (BDS) beam-line, shown in Fig 2, the crab cavities are positioned between 13.4 and 17.4 metres from the IP. At the position of the crab cavities R_{12}=16.4 m/rad and R_{34}=2.4 m/rad. At the IP the bunches are focussed to σ_x=655 nm.and σ_y=5.7 nm and the bunch length is σ_z=300 μm. The bunch charge is 3.2 nC and the machine operates with 5 Hz train repetition frequency and 2820 bunches per train with ~308 ns between each bunch. For these parameters, (9) shows the cavity will be required to be aligned to better than 7 mrad to keep the luminosity loss below 2%.

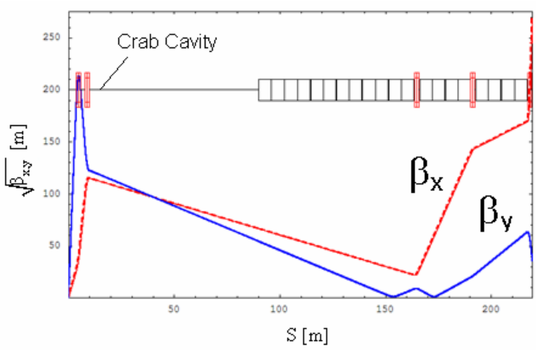

FIG. 2. The ILC BDS lattice showing the Beta functions.

The ILC crab cavity has a phase tolerance of 100 milli-degrees, assuming a similar tolerance we could have a gradient of up to 2MV/m for a maximum luminosity loss of 2% from (12). Using (10) we can show that a single cell anti-crab cavity will provide enough voltage to cancel the effect of roll misalignments of up to 65 mrad~3.72 degrees in the ILC crab cavities.

Microwave studio has been used to model a single cell anti-crab cavity. The cavity has an equator radius of 47.6mm with two 1.5 mm indentations on either side in one polarisation to lift the degeneracy of the dipole modes. The indentations cause a 10 MHz frequency shift between the two polarisations of the 1st dipole mode. The cavity has a large iris radius, 18mm, to allow the HOMs to be strongly damped.

The dipole mode of this cavity has an R/Q of 13.6 Ω/cm^2 as does the same-order mode. At a gradient of 2 MV/m the peak electric field is 7.76 MV/m and the peak magnetic flux density is 58.4 mT. This cavity has a geometry factor, G, of 193 Ω. As the cavity is likely to be operating at low gradients, this cavity could possibly operate normal conducting as it will have low thermal loading at the required 0.5% duty factor.

The wakefields in this cavity are likely to be negligible in comparison to the crab cavity as it is only a single cell and will have loaded Q's at least an order of magnitude lower if superconducting and much lower if normal conducting.

IV. TRACKING AND BEAM-BEAM SIMULATIONS

In order to verify that the anti-crab cavity corrected for rotational misalignments, a series of simulations of the ILC Beam delivery system (BDS) were performed. This was verified by integrating the particle tracking code PLACET into the beam-beam code GUINEA-PIG, which was used to calculate the luminosity of the colliding bunches of electrons and positrons.

The program PLACET (Program for Linear Accelerator Correction Efficiency Tests) is a tracking code that is used to simulate transverse and longitudinal beam transport in linear accelerators. With this program it is possible to simulate the dynamic effects of a beam in the beam delivery system of the ILC, including the crab cavity. PLACET takes into account collective effects such as long and short range cavity wakefields, resistive and geometric wakefields in the collimators and synchrotron radiation emission in all magnetic elements. Imperfections such as misalignments, phase and amplitude errors as well as roll angles are also taken into account. In the beam delivery system, each bunch is split up into several macro-particles with each macro-particle representing thousands of electrons/positrons.

The bunches were tracked to the IP using PLACET at which point a rotation of the axis by 7 mrad was implemented into the electron positions mathematically using OCTAVE, hence creating a 14 mrad crossing angle in the simulations.

The beams in the ILC and CLIC will be focused to very small sizes at the IP, hence the electro-magnetic fields of each bunch will have a strong effect on each other causing bunches of opposite charge to attract each other. In the presence of bunch rotations or offsets this beam-beam interaction leads to a mutual focusing which increases luminosity. However if the beam-beam forces are too strong this can lead to instabilities which will decrease the luminosity. The beam-beam interaction was simulated using the code GUINEA-PIG (Generator of Unwanted Interactions for Numerical Experiment Analysis - Program Interfaced to GEANT). The phase space parameters of each macro-particle in the positron and electron bunches are passed to GUINEA_PIG to calculate the luminosity. In the simulations 80,000 macro-particles per bunch were used. This number guarantees numerical stability to the GUINEA-PIG calculations.

First the effect of a roll misalignment on the crab cavity was calculated. A single 9 cell crab cavity was simulated at a voltage of 1.2936 MV in order to achieve the 7 mrad bunch rotation. The horizontal rotation at the IP is shown in Fig 3.

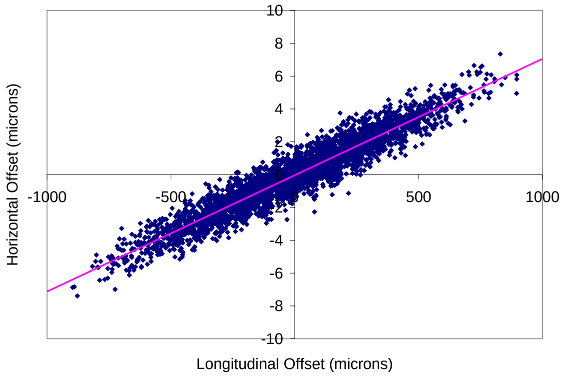

FIG. 3. The horizontal offset against longitudinal position for the macro-particles in a bunch at the IP of the ILC.

Then a rotational misalignment of 10 mrad was used on one of the crab cavities and a rotation of the bunch in the y-z plane was observed, shown in Fig. 4. This causes a vertical rotation of 17 μrad, which would cause a 30% luminosity loss with the ILC bunch size.

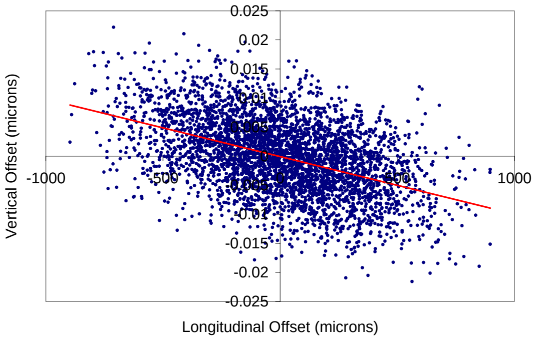

FIG. 4. The vertical offset against longitudinal position for the macro-particles in a bunch at the IP of the ILC where the crab cavity has a 10 mrad roll misalignment.

The bunch rotation was then systematically varied and the luminosity was recorded. In the simulations the cavity on one of the beam-lines was rotated, and the luminosity was calculated as a function of misalignment, shown in Fig 5. It was found that a roll alignment of 1.1 mrad is required to keep the luminosity loss below 2%. The difference in the simulations compared to the geometric calculations is due to beam-beam effects.

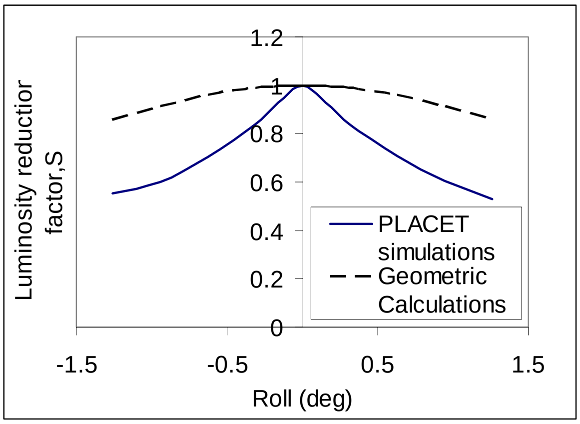

FIG. 5. Luminosity Reduction factor for various roll misalignments of the ILC crab cavities comparing simulations and analytic calculations.

In order to correct for this effect an anti-crab cavity with a deflecting voltage of 13 kV, was simulated in the beam delivery system next to the crab cavity. It was found that 100% of the luminosity was recovered and the rotation on the bunch was no longer visible, as can be seen in Figure 6.

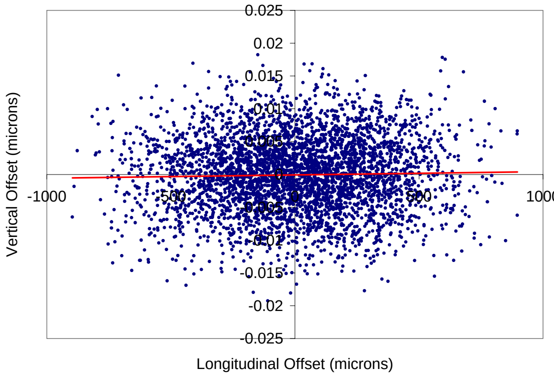

FIG. 6. The vertical offset against longitudinal position for the macro-particles in a bunch at the IP of the ILC where the crab cavity has a 10 mrad roll misalignment and there is an anti-crab cavity correction.

Next the effect of phase and amplitude variations on the anti-crab cavity was investigated. The cavities on both beam-lines were misaligned by 10 mrad and the luminosity of the collisions was calculated as the voltage of the anti-crab cavity on one of the beam-lines was varied between -0.013 MV and 0.013 MV. As can be seen in Fig. 7 a 20% variation in voltage results in a 5% luminosity reduction. This is unlikely to be an issue as modern accelerators tend to have amplitude stability of better than a few percent.

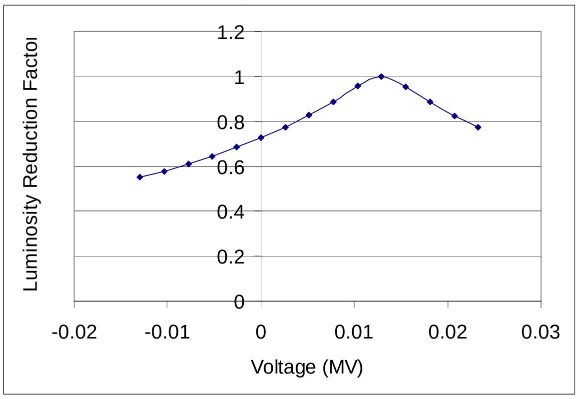

FIG. 7. Luminosity Reduction factor as a function of the amplitude error on one anti-crab cavity for a 10 mrad roll misalignment of the ILC crab cavity.

To investigate the effect on luminosity of phase variations in the anti-crab cavity the anti-crab cavity voltage was set for maximum luminosity for a number of crab cavity roll misalignments. Then the phase of one of the anti-crab cavities was varied and the luminosity was calculated, shown in Fig 8. With a roll misalignment of 100 mrad a 0.1 deg phase error, similar to the specifications for the ILC crab cavity, reduced the luminosity by 12%. For a 22mrad misalignment a 0.1 deg phase error resulted in a 1.5% luminosity loss. The difference with respect to the analytical results is due to beam-beam effects.

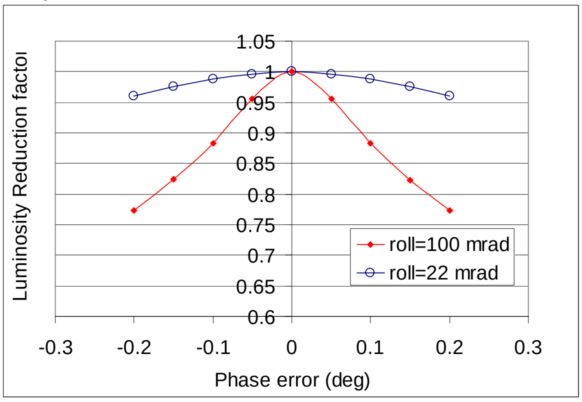

FIG. 8. Luminosity Reduction factor as a function of the phase error on one anti-crab cavity for various roll misalignments of the ILC crab cavity.

V. CONCLUSION

It has been shown, in this paper, that a misalignment of the crab cavities in an accelerator can produce an unwanted vertical crabbing/rotation of the beam. For the ILC crab cavities a 10 mrad roll misalignment on one cavity can cause the loss of 30% of the luminosity.

One possible solution is to implement an anti-crab cavity to remove the vertical momentum imparted to the particles. The operation of such a scheme has been simulated in PLACET and has been shown to recover 100% of the luminosity lost due to roll misalignments. Such a system has a limited range of correction, ~30 mrad for the ILC for a maximum 2% luminosity reduction due to phase errors, and would need to work in tandem with a mechanical tuning mechanism with a larger range but with less accuracy for the correction of roll misalignments. However at 100 mrad roll misalignment a luminosity reduction due to phase errors is only around 12% which is far less than the reduction in luminosity without any roll correction.

It is shown that for the beam parameters of the ILC the simple geometric approximations are not sufficient and full simulations, including beam-beam effects are required.

The anti-crab cavity needn't be a SCRF cavity it could also be a simple NCRF cavity such as the type used for beam diagnostics. This would keep the cost of such a tool low.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Leo Bellantoni, FNAL and Mr Mike Dykes, STFC for many useful discussions on this work.

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