A BEAM-BASED HIGH RESOLUTION PHASE IMBALANCE MEASUREMENT METHOD FOR THE ILC CRAB CAVITIES*

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Abstract

A beam-based test bench is proposed for the ILC Crab Cavity system. The RF phase and amplitude imbalance in the pair of the electron and positron cavities, a harmful spurious odd field component, and some effects of beam-induced field can be measured and investigated.

The test bench comprises two fully powered crab cavities, a RF reference distribution circuit, two upstream reference BPMs and two downstream BPMs measuring the imbalance differential kick produced to a traversing low energy bunch. The set-up is insensitive to bunch arrival time jitter and RF phase Common Mode jitter. With two pairs of BPMs, it is insensitive to bunch trajectory jitter as well.

Similar BPM set-up with single dipole cavity can be used as a high resolution bunch arrival time jitter monitor.

INTRODUCTION

In the ILC crab cavity system, for 20mrad crossing angle the phase and amplitude imbalance of the electron and positron crab cavities must be within 0.02° (1.3GHz) and a few 10^{-2} respectively. [1] The phase tolerance is a challenge. We propose to test the ILC crab cavity system on some available low energy beam. First, a beam-based test bench would be a powerful investigation instrument. Second, final test could be done in advance to the ILC to ensure crab cavity system's availability for service.

We propose a test bench that comprises two fully powered ILC crab cavities and the RF reference distribution circuit that will be used in the ILC. The upstream and downstream pairs of spaced BPMs measure the differential kick produced to a traversing bunch when the cavities are in imbalance. To achieve resolution 0.01° of the test bench with conventional BPMs, a beam of low energy (a few GeV) should be used.

A conclusive and decisive test could be done on the 5GeV beam in the ILC Damping Ring Extraction Line. In advance to its availability, beams from FEL linacs could be used. One of them, the ERL 4GLS now under design in Daresbury Laboratory, has one of its beams as 1GeV 1nC bunches of repetition rate up to 1kHz.

In this paper we describe a test bench set-up and derive expressions for the differential kick. Using even and odd components of the magnetic field longitudinal envelope, we find that for the ILC a requirement to the spurious odd component is tight, and show that each component can be individually measured on the bench. Effects appearing from beam-induced field can also be investigated to some extent. We also examine a spin-off of the set-up. It is a high resolution bunch arrival time monitor based on single dipole cavity.

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TEST BENCH SET-UP

The test bench block diagram is shown in Fig. 1. The master oscillator MO is phase-locked to bunches. The phase of the RF signal as regards to bunches can be varied with the phase shifter PHS. The dipole crab cavities C1 and C2 are excited through the RF reference distribution circuit RDC. The distance between the longitudinal centres of the cavities is d. The phase and amplitude in each cavity can be varied using the stabilisation feedback reference inputs PH1 and PH2 and AM1 and AM2 respectively. The initial bunch trajectory is measured by BPM1 and BPM2 spaced by L_{12}. The trajectory after the cavities is measured by BPM3 and BPM4 spaced by L_{34}.

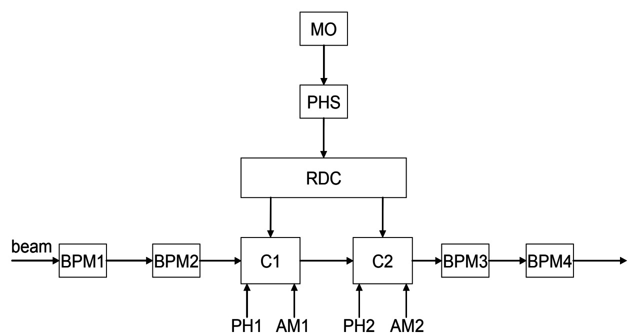

Figure 1: The Test Bench block diagram

For calculation of kick use a simplified model where cavity magnetic field only is taken into account. The vertical magnetic field in each cavity is:

$$B_{y1}(z,t) = (1+\delta a)\cdot[B_y(z)+b_y(z)]\times \times\sin[\omega(t+\delta t)+(\varphi+\Delta\varphi)] \quad (1)$$

$$B_{y2}(z,t) = (1-\delta a)\cdot[B_y(z)-b_y(z)]\times \times\sin\left[\omega\left(t+\delta t-\frac{d}{c}\right)+(\varphi+\Delta\varphi)+\delta\varphi\right] \quad (2)$$

where $B_y(z) = (B_{y1}(z)+B_{y2}(z))/2$, $b_y(z) = (B_{y1}(z)-B_{y2}(z))/2$, δa is the amplitude imbalance, δt is the bunch arrival time jitter, φ is the phase set in the PHS, $\Delta\varphi$ is some phase variation, $\delta\varphi$ is the phase imbalance. Take $|b_y(z)|/|B_y(z)| << 1$, $|\delta a| << 1$, $|\Delta\varphi| << 1$, $|\delta\varphi| << 1$.

The total horizontal kick θ received by the bunch center of mass is

$$\theta = \theta_1 + \theta_2 = \frac{(p_{\perp 1} + p_{\perp 2})\cdot c}{E} \quad (3)$$

where $p_{\perp 1}$ and $p_{\perp 2}$ are the transverse momenta, E/c is the longitudinal momentum. Using (1) and (2) and neglecting second order infinitesimals, the kick is

$$\theta = -\frac{ec}{E}\cdot\int_{-\infty}^{+\infty}\left\{B_y(z)\cdot\left(\delta\varphi - 2\pi\frac{\delta d}{\lambda}\right)\cdot\cos\left(\omega\frac{z}{c}+\varphi\right) + \right.$$
$$\left. + \left[2\cdot\delta a\cdot B_y(z) + 2b_y(z)\right]\sin\left(\omega\frac{z}{c}+\varphi\right)\right\}\cdot dz \quad (4)$$

So, the total kick is some measure of the phase imbalance in two crab cavities. It contains also an amplitude imbalance and an envelope difference term. The kick is measured with BPMs as the trajectory kick:

$$\theta_{\text{BPM}} = \frac{X_2 - X_1}{L_{12}} - \frac{X_4 - X_3}{L_{34}} \quad (5)$$

where X_1 to X_4 are the BPM bunch position readings (provided BPM zero offsets are subtracted).

From (4) it is seen that in this set-up the total kick is independent on bunch arrival time jitter and master oscillator phase jitter. Besides, use of two pairs of BPM makes the kick measured independent on bunch trajectory jitter.

In the expression (4) the distance d has been taken as

$$d = (2k+1)\cdot\frac{\lambda}{2} + \Delta d,\ k = 1, 2, ... \quad (6)$$

where λ is the RF wavelength, and $\Delta d << \lambda$. Taking

$$\Delta d = \overline{\Delta d} + \delta d \quad (7)$$

where $\overline{\Delta d}$ is a systematic error and δd represents variations, and assuming that the systematic error can be compensated by phase tuning at the inputs PH1 and PH2, one can use (6) with δd instead of Δd as it is done in (4).

Take each $B_y(z)$ and $b_y(z)$ as a sum of even and odd functions [2]:

$$B_y(z) = B_{\text{e}}(z) + B_{\text{o}}(z) \quad (8)$$

$$b_y(z) = b_{\text{e}}(z) + b_{\text{o}}(z) \quad (9)$$

The total kick (4) expressed through respective even/odd components is:

1. For the case $\varphi = 0$

$$\theta_0 = (\theta_{\text{e}} + \theta_{\text{o}})\big|_0 = \left(\delta\varphi - 2\pi\frac{\delta d}{\lambda}\right)\cdot C + 2\cdot\delta a\cdot S + 2s \quad (10)$$

2. For the case $\varphi = \pi/2$

$$\theta_{\pi/2} = (\theta_{\text{e}} + \theta_{\text{o}})\big|_{\pi/2} = 2\cdot\delta a\cdot C + 2c - \left(\delta\varphi - 2\pi\frac{\delta d}{\lambda}\right)\cdot S \quad (11)$$

where the kick integrals are:

$$-\frac{ec}{E}\cdot\int_{-\infty}^{+\infty} B_{\text{e}}(z)\cdot\cos\omega\frac{z}{c}\cdot dz = C \quad (12)$$

$$-\frac{ec}{E}\cdot\int_{-\infty}^{+\infty} B_{\text{o}}(z)\cdot\sin\omega\frac{z}{c}\cdot dz = S \quad (13)$$

$$-\frac{ec}{E}\cdot\int_{-\infty}^{+\infty} b_{\text{e}}(z)\cdot\cos\omega\frac{z}{c}\cdot dz = c \quad (14)$$

$$-\frac{ec}{E}\cdot\int_{-\infty}^{+\infty} b_{\text{o}}(z)\cdot\sin\omega\frac{z}{c}\cdot dz = s \quad (15)$$

The kick integrals can be measured with beam. In each case $\varphi = 0$, $\varphi = \pi/2$, using the inputs PH1 and PH2, AM1 and AM2, set some large phase or/and amplitude imbalance:

$$\tilde\varphi_1 = -\tilde\varphi_2 = \tilde\varphi, \quad |\tilde\varphi| >> \left|\delta\varphi - 2\pi\frac{\delta d}{\lambda}\right| \quad (16)$$

$$\tilde a_1 = -\tilde a_2 = \tilde a, \quad |\tilde a| >> |\delta a| \quad (17)$$

and measure the resulting kicks $\tilde\theta_{1,2}\big|_0$ and $\tilde\theta_{1,2}\big|_{\pi/2}$. The kick integrals can be found from (10) and (11) as

$$C = \left.\frac{\tilde\theta_1 - \tilde\theta_2}{2\tilde\varphi}\right|_{0,\ \tilde a_1 = \tilde a_2 = 0} = \left.\frac{\tilde\theta_1 - \tilde\theta_2}{2\tilde a}\right|_{\pi/2,\ \tilde\varphi_1 = \tilde\varphi_2 = 0} \quad (18)$$

$$S = \left.\frac{\tilde\theta_1 - \tilde\theta_2}{2\tilde a}\right|_{0,\ \tilde\varphi_1 = \tilde\varphi_2 = 0} = -\left.\frac{\tilde\theta_1 - \tilde\theta_2}{2\tilde\varphi}\right|_{\pi/2,\ \tilde a_1 = \tilde a_2 = 0} \quad (19)$$

$$c = \left.\frac{\tilde\theta_1 + \tilde\theta_2}{4}\right|_{\pi/2,\ \tilde\varphi_1 \& \tilde a_1,\ \tilde\varphi_2 \& \tilde a_2} \quad (20)$$

$$s = \left.\frac{\tilde\theta_1 + \tilde\theta_2}{4}\right|_{0,\ \tilde\varphi_1 \& \tilde a_1,\ \tilde\varphi_2 \& \tilde a_2} \quad (21)$$

For the bunch repetition rate f the mean and the standard deviation of each (10) and (11) can be found as well as the spectra in the bandwidth up to $f/2$.

Assume C and S are constants, and $S/C << 1$. Also $c/C << 1$ and $s/C << 1$. The envelope difference and the distance can vary due to some microphonic effects, so the standard deviations are $\sigma_c \sim c$, $\sigma_s \sim s$ and $\sigma_{\delta l} \neq 0$. Taking the test bench phase resolution as $\sigma_{\delta\varphi}$, write:

$$\sigma_{\theta_0}{}^2 = C^2\cdot\sigma_{\delta\varphi}{}^2 + 4\pi^2\cdot C^2\cdot\frac{\sigma_{\delta l}{}^2}{\lambda^2} + 4S^2\cdot\sigma_{\delta a}{}^2 + 4s^2 \quad (22)$$

So, to achieve the phase resolution $\sigma_{\delta\varphi}$, the distance variation, the amplitude variation and the envelope difference variation should be sufficiently small in the bandwidth $f/2$ to have

$$\left(\pi^2\cdot\frac{\sigma_{\delta l}{}^2}{\lambda^2} + \frac{S^2}{C^2}\cdot\sigma_{\delta a}{}^2 + \frac{s^2}{C^2}\right) < \frac{1}{4}\cdot\sigma_{\delta\varphi}{}^2 \quad (23)$$

EVEN AND ODD COMPONENTS

Estimate the odd component kick that is tolerable for ILC operation. At the exit of a perfectly phased crab cavity with the field

$$B_{y1}(z,t) = \left[B_{\text{e}}(z) + B_{\text{o}}(z)\right]\cdot\sin\omega t \quad (24)$$

the kick to a particle is:

$$\vartheta = 2\pi \cdot \frac{l}{\lambda} \cdot C_{\mathrm{ILC}} + S_{\mathrm{ILC}} \tag{25}$$

where C_{ILC} and S_{ILC} are the kick integrals calculated as (12) and (13). The first term is the kick producing bunch rotation, l is the distance between the bunch center of mass and the particle. Using relation $2\pi \cdot (l/\lambda) \cdot C_{\mathrm{ILC}} = \alpha \cdot (l/D)$ where α is half of the crossing angle, the first kick integral can be expressed as

$$C_{\mathrm{ILC}} = \frac{\alpha}{2\pi} \cdot \frac{\lambda}{D} \tag{26}$$

where D is the drift distance from the crab cavity exit to the IP.

The second integral causes a bunch center of mass offset Δx from the IP:

$$\Delta x = S_{\mathrm{ILC}} \cdot D \tag{27}$$

To avoid ILC's luminosity deterioration, either the offset caused by each cavity should be $|\Delta x_1|, |\Delta x_2| << \sigma_x$ where σ_x is the beam size, or at least, the offsets being large, should be stable within $\xi \cdot \sigma_x$, $\xi << 1$. To illustrate the first condition, take ratio:

$$\varsigma = \frac{|S_{\mathrm{ILC}}|}{|C_{\mathrm{ILC}}|} << \frac{2\pi}{\alpha} \cdot \frac{\sigma_x}{\lambda} \tag{28}$$

For $2\alpha = 20\mathrm{mrad}$, $\sigma_x \sim 500\mathrm{nm}$, $\lambda = c/1.3\mathrm{GHz}$ the ratio is to be $\varsigma << 1.5 \cdot 10^{-3}$. The second condition gives:

$$\frac{|\delta S_{\mathrm{ILC}}|}{|C|} \le \xi \cdot \frac{2\pi}{\alpha} \cdot \frac{\sigma_x}{\lambda} = \xi \cdot 1.5 \cdot 10^{-3} \tag{29}$$

Even this relaxed condition to the odd component is tight.

EFFECTS OF BEAM-INDUCED FIELD

The dipole field induced by a bunch in a cavity is proportional to bunch intensity and bunch offset from the cavity center. A low energy bunch traversing a cavity perfectly phased to the bunch gets displacement:

$$\Delta x(z) = \frac{ec}{E} \cdot \int_{-\infty}^{z} \int_{-\infty}^{\tau} B_y(\chi) \cdot \sin \omega \frac{\chi}{c} \cdot d\chi \cdot d\tau \tag{30}$$

Assume that the bunch initial trajectory can be shifted by $[-\Delta x(z_{\mathrm{ex}})/2]$ where z_{ex} is the first cavity exit. With this offset the bunch getting displacement (30) in each cavity, passes just through both of the cavity centers. In this case, in a first approximation, net induced field in each cavity can be taken zero. For $\delta\varphi - 2\pi \cdot (\delta d/\lambda) \ne 0$ and $\delta\alpha \ne 0$ the bunch misses the centers. The induced field causes some additional phase/amplitude imbalance of magnetic field vectors in the cavities, and additional kick occurs.

The single bunch imbalance effect is low as the beam-induced field is considerably lower than the driving field. For a beam with ILC pattern the effect may be much stronger as the cavities store the dipole mode energy from sequential adjacent bunches.

Varying bunch intensity and offset, beam-induced imbalance effects can be identified and investigated.

TEST BENCH BEAM ENERGY

Write the test bench phase resolution $\sigma_{\delta\varphi}$ as

$$\sigma_{\delta\varphi} = \frac{1}{\sqrt{2}} \cdot \frac{\sigma_{\mathrm{BPM}}}{L} \cdot \frac{1}{C} \tag{31}$$

where σ_{BPM} is the single bunch BPM position resolution, $L_{12} = L_{34} = L$. Using relation $C/C_{\mathrm{ILC}} = E_{\mathrm{ILC}}/E$ and the expression (26) as well, the test bench energy E can be expressed as

$$E \le E_{\mathrm{ILC}} \cdot \sqrt{2} \cdot \sigma_{\delta\varphi} \cdot \frac{L}{\sigma_{\mathrm{BPM}}} \cdot \frac{\alpha}{2\pi} \cdot \frac{\lambda}{D} \tag{32}$$

Take $E_{\mathrm{ILC}} = 500\mathrm{GeV}$. To achieve $\sigma_{\delta\varphi} \le 0.01°$, with the BPM resolution $\sigma_{\mathrm{BPM}} = 1\mu\mathrm{m}$, and the distances $L = 5\mathrm{m}$, $D \sim 50\mathrm{m}$, the test bench beam energy should be $E \le 5\mathrm{GeV}$.

THE SET-UP AS A BUNCH ARRIVAL TIME MONITOR

The set-up in Fig. 1 with single dipole cavity can be used as a high resolution bunch arrival time monitor. For the magnetic field taken as

$$B_y(z,t) = (1+\delta a) \cdot [B_{\mathrm{e}}(z) + B_{\mathrm{o}}(z)] \times \times \sin[\omega(t+\delta t) + (\varphi + \delta\varphi)] \tag{33}$$

the kick is:

$$\theta = [(\omega \cdot (t_a + \delta t) + \delta\varphi) \cdot C + \delta a \cdot S] \cdot \cos\varphi \tag{34}$$

where t_a is the time of bunch arrival at the longitudinal center of the cavity, δt is the arrival time jitter. For $\omega = 2\pi \cdot 1.3\mathrm{GHz}$ and the RF phase noise $\sigma_{\delta\varphi} \le 0.01°$ the monitor resolution estimate $\sigma_{\delta t}$ is a few tens of fs provided the RF amplitude is sufficiently stable: $\sigma_{\delta a} \le \sigma_{\delta\varphi} \cdot |C|/|S|$.

SUMMARY

It is shown that on a beam-based ILC crab cavity test bench proposed the phase imbalance can be verified, the harmful spurious odd field component can be measured, and some effects of beam-induced field can be investigated. Using some low energy beam, these tests can be done in advance to the ILC.

It is also shown that a high resolution bunch arrival time monitor can be built using two pairs of BPM and a dipole cavity.

REFERENCES

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