Nuclear Instruments and Methods in Physics Research A 728 (2013) 53–58

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A metrology system for a high resolution cavity beam position monitor system

Sean Walston [g,*], Stewart Boogert [d], Carl Chung [g], Pete Fitsos [g], Joe Frisch [i], Jeff Gronberg [g], Hitoshi Hayano [k], Shantell Hinton [i], Yosuke Honda [k], Oleg Khainovski [b], Yury Kolomensky [b], Peter Loscutoff [b], Alexey Lyapin [h], Stephen Malton [h], Justin May [i], Douglas McCormick [i], Robert Meller [f], David Miller [h], Toyoko Orimoto [b,j], Marc Ross [i,a], Mark Slater [c], Steve Smith [i], Tonee Smith [i], Nobuhiro Terunuma [k], Mark Thomson [c], Junji Urakawa [k], Vladimir Vogel [e], David Ward [c], Glen White [i]

[a] *Fermi National Accelerator Laboratory, Batavia, IL, USA*
[b] *University of California and Lawrence Berkeley National Laboratory, Berkeley, CA, USA*[1]
[c] *University of Cambridge, Cambridge, UK*[2]
[d] *Royal Holloway, University of London, Egham, UK*
[e] *Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[f] *Cornell University, Ithaca, NY, USA*[3]
[g] *Lawrence Livermore National Laboratory, 7000 East Ave., L-181, Livermore, CA 94550, USA*[4]
[h] *University College London, London, UK*[2]
[i] *Stanford Linear Accelerator Center, Menlo Park, CA, USA*[5]
[j] *California Institute of Technology, Pasadena, CA, USA*
[k] *High Energy Accelerator Research Organization (KEK), Tsukuba-shi, Ibaraki-ken, Japan*[6]

ARTICLE INFO

Article history:
Received 16 May 2013
Accepted 28 May 2013
Available online 21 June 2013

Keywords:
Cavity Beam Position Monitor (BPM)
Accelerator Test Facility (ATF)
International Linear Collider (ILC)

ABSTRACT

International Linear Collider (ILC) interaction region beam sizes and component position stability requirements will likely be as small as a few nanometers. It is important to the ILC design effort to demonstrate that these tolerances can be achieved–ideally using a beam-based stability measurement. We developed a high resolution RF cavity Beam Position Monitor (BPM) system. A triplet of these BPMs, installed in the extraction line of the KEK Accelerator Test Facility (ATF) and tested with its ultra-low emittance beam, achieved a position measurement resolution of 15 nm. A metrology system for the three BPMs was subsequently installed. This system employed optical encoders to measure each BPM's position and orientation relative to a zero-coefficient of thermal expansion carbon fiber frame. We have demonstrated that the three BPMs behave as a rigid-body at the level of less than 5 nm.

1. Introduction

The design for the International Linear Collider (ILC) calls for beams which are focused down to a few nanometers at the interaction point. This poses unique engineering challenges which must be overcome. To wit, final focus components must be effectively stabilized at the level of a few nanometers. With nanometer resolution Beam Position Monitors (BPMs), mechanical stability can be measured relative to the particle beam itself. The intent of our experiment was to understand the limits of BPM performance and to evaluate their role in overcoming some of the thorny engineering issues the interaction region of the ILC presents.

2. Theory of cavity BPMs

When a bunch transits a cavity BPM, the field of the bunch excites the eigenmodes of the electromagnetic fields within the

* Corresponding author. Tel.: +925 423 7364; fax: +925 423 3371.
E-mail address: walston2@llnl.gov (S. Walston).
[1] This work was supported in part by the US Department of Energy under Contract DE-FG02-03ER41279.
[2] This work was supported by the Commission of the European Communities under the 6th Framework Programme “Structuring the European Research Area,” Contract number RIDS-011899.
[3] This work was supported by the National Science Foundation.
[4] This work was performed under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.
[5] This work was supported by the US Department of Energy under Contract DE-AC02-76SF00515.
[6] This work was supported by the Japan–USA Collaborative Research Grant, Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science.

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.05.196

cavity. The amplitude of the TM_{110} mode has a linear dependence on the transverse offset of the beam relative to the electrical center of the cavity; the phase depends on the direction of the offset. The TM_{110} mode also has a linear dependence on both the angle of attack and angle of obliquity (collectively referred to as "tilt") of a finite length bunch relative to the z-axis of the cavity. This is discussed in more detail elsewhere [1–3].

The intrinsic resolution of a BPM is limited by the signal to noise ratio of the system. The signal voltage of the BPM is determined by the beam's energy loss to the TM_{110} mode and by the external coupling of the waveguide; the overall noise of the system comes from thermal noise as well as contamination from the symmetric TM_{010} mode. It has been estimated that an RF cavity BPM could have a resolution below 1 nm [4].

3. Experiment

This experiment employed three identical cavity BPMs with a nominal dipole (TM_{110}) mode frequency of 6426 MHz. The BPMs were rigidly mounted to the endplates of an alignment frame by six variable-length struts which allowed for movement by small amounts in x, y, z, yaw, pitch, and roll for the purposes of aligning and calibrating. The alignment frame in turn was mounted by four variable-length motorized legs which allowed movement in x, y, yaw, pitch, and roll for the purpose of steering the experiment onto the beam.

Single bunch extractions from the ATF ring of typically between 6 and 7×10^9 e^- at an energy of 1.28 GeV were used for these tests. The machine repetition rate was ~1 Hz.

Because the beam passed through the apparatus in a straight line, the beam's position in BPM 2 was related in a linear way to the beam's positions in BPMs 1 and 3. BPM resolution was determined by measuring the residual—that is the difference between the position of the beam as measured by BPM 2 and the predicted position as calculated from the beam's parameters measured by BPMs 1 and 3. The coefficients used to calculate the beam's position at BPM 2 were determined by regressing the beam's y position measured by BPM 2, y_2^{beam}, against $x_{1,3}^{\text{beam}}$, $y_{1,3}^{\text{beam}}$, $x_{1,3}^{\prime\text{beam}}$ and $y_{1,3}^{\prime\text{beam}}$ over many events. The resolution was then proportional to the standard deviation of the distribution of the residuals for many ATF extractions. Details of the experiment and explanations of the waveform processing, calibration, and resolution algorithms are all discussed in detail elsewhere [3].

4. Metrology system

A metrology system, installed in January 2006, was intended to make possible an evaluation of the non-rigid-body mechanical motion among the three BPMs including that part due to thermal drifts. The complete experiment with the metrology system is shown schematically in Fig. 1. A photograph of the NanoBPM experiment with the metrology system installed is shown in Fig. 2.

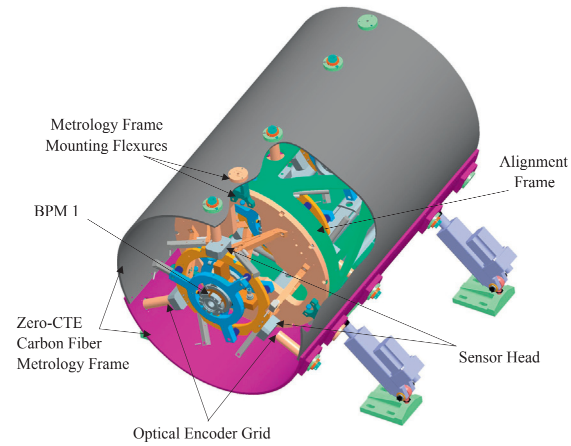

Fig. 1. The metrology system encloses the NanoBPM experiment in a zero-coefficient of thermal expansion carbon fiber metrology frame.

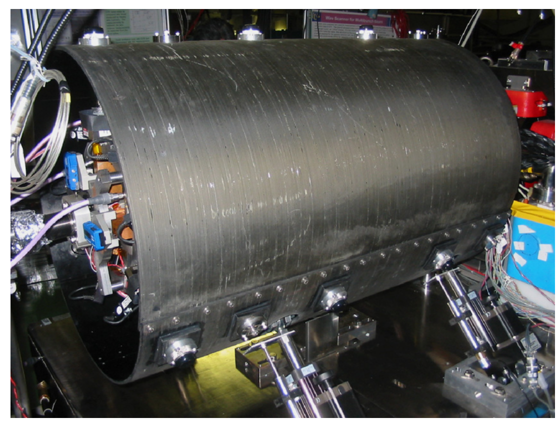

Fig. 2. The NanoBPM experiment enclosed in the metrology system.

4.1. Design and construction

The metrology system employed a total of nine NanoGrid Model A Hi-Resolution systems, manufactured by Optra Inc. [5]. The Optra NanoGrid is an xy metrology system that measures the position of a sensor head relative to an optical encoder grid consisting of a two-dimensional, 10 micron pitch diffraction grating on soda-lime glass. Each sensor head, which contained a diode laser source, imaged the two interference patterns onto 90-element triple detector arrays to make very accurate phase measurements. When the encoder grid moved relative to the sensor head, the fringes moved across the detector arrays generating R, S and T signals which were 120° apart in phase. These three signals made possible a phase measurement which was independent of the laser power, the reflectivity of the grid, and the relative intensities in the ± 1 diffracted orders. This approach made possible a shot-noise-limited phase resolution of 1 part in 2^{14} corresponding to a measurement resolution of 0.305 nm.

Three NanoGrid sensor heads were attached to the mounting rings of each BPM at 120° angles (similar to the hood ornament on a Mercedes-Benz): Sensor head number 1 corresponded to the 12 o'clock position, sensor head 2 to the 4 o'clock position, and sensor head 3 to the 8 o'clock position as viewed looking down the beamline towards the beam dump. The encoder grids were supported by NanoGrid support tubes which in turn were attached to the metrology frame. This is shown in Fig. 3.

The metrology frame and NanoGrid support tubes were constructed of Carbon Fiber Reinforced Plastic (CFRP). This material is light, stiff, and its thermal expansion can be altered by adjusting the angle of the plies and the composition of the materials. The winding of the metrology frame and NanoGrid support tubes was done by Aerojet [6].

Thermally induced radial movement of the encoder grids was minimized by using the axial elongation of the NanoGrid support tubes to offset the increase in the radius of the metrology frame. These thermally induced changes were simulated using Pro/ENGINEER Mechanica [7] and included all mounting flexures and NanoGrid support tubes. The degree of thermal growth was adjusted by varying the laminate ply angles of both the metrology