Introduction to High-Resolution Accelerator Alignment Using X-ray Optics

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A novel alignment technique utilizing the x-ray beam of a dedicated alignment undulator in conjunction with pinholes and position-sensitive detectors for positioning accelerator components in an x-ray free-electron laser will be presented. In this concept two retractable pinholes at each end of the main undulator line define a stable and reproducible x-ray beam axis (XBA). Targets are precisely positioned on the XBA using a pinhole camera technique. Position-sensitive detectors responding to both x-ray and electron beams enable the direct transfer of the position setting from the XBA to the electron beam. This system has the potential to deliver superior alignment accuracy in the micron range for target pinholes in the transverse directions over long distances. It defines the beam axis for the electron-beam–based alignment with high reproducibility. This concept complements the electron-beam–based alignment and the existing survey methods advancing the alignment accuracy of long accelerators to an unprecedented level. Further improvements of the transverse accuracy using x-ray zone plates and a concurrent measurement scheme during accelerator operation, providing real-time feedback for transverse position corrections, will be discussed.

1. INTRODUCTION

Several large-scale linear accelerator projects are under construction or have been proposed. The Linear Coherent Light Source (LCLS) [1] utilizes parts of the existing linear accelerator at SLAC followed by a 130-m-long undulator section with a 6.8-mm fixed gap. DESY is planning to build an x-ray free-electron laser (XFEL) [2] with a total length on the order of 3.3 km for multiple undulator sections of which the longest is about 300 m with a gap ranging from 6 to 20 mm. A proposal by Spring8 to establish the SCSS [3] will use a 1-GeV, 55-m-long accelerator followed by a 22.5-m-long in-vacuum undulator section with a 3.7-mm gap. Finally, PAL at POSTECH in South Korea is proposing the PAL/XFEL [4] with a 60-m in-vacuum variable-gap undulator with a minimum gap of 3 mm. The Compact Linear Collider (CLIC) at CERN has a 10 μm alignment tolerance within sections of 200 m in the long main linac that will be 38 km long at full energy [5].

These projects all require precision alignment of beamline components at unprecedented accuracy. The first step in aligning a linear accelerator is establishing a straight line reference (SLR). However, establishing such a reference system with an rms error below 0.1 mm over 100 – 1000 m is difficult using conventional surveying techniques [6]. It is a well-known fact that, using successive setups, random alignment errors propagate as the square root of the number of setups, while the systematic errors propagate linearly as shown in Figure 1. Once the cross-over point between the random and systematic propagation is reached, the systematic effects dominate the results and will be noticeable over long distances. One may also note that, even if the accuracy of the multi step survey technique were to improve dramatically, the diffusive ground motion, roughly described by the ATL law [7], would render the system useless over long periods of time since the technique relies heavily on survey targets fixed on the accelerator tunnel. For this reason, a high-accuracy SLR has to be established with a single setup. It has long been realized that such an SLR can be established with a light beam since it propagates in straight lines. A number of alignment concepts based on this principle have been constructed or proposed.

In 1968 W. Herrmannsfeldt [8] and others proposed and implemented a precision straight-line alignment system utilizing Fresnel lenses for the 3-km-long Stanford linear accelerator. The system uses a HeNe laser light source, a detector, and rectangular Fresnel lenses attached to accelerator girders projecting the light beam onto the detector.

Deviations relative to an initial straight-line setup can be measured with an estimated transverse accuracy on the order of ±25 μm over the length of the accelerator.

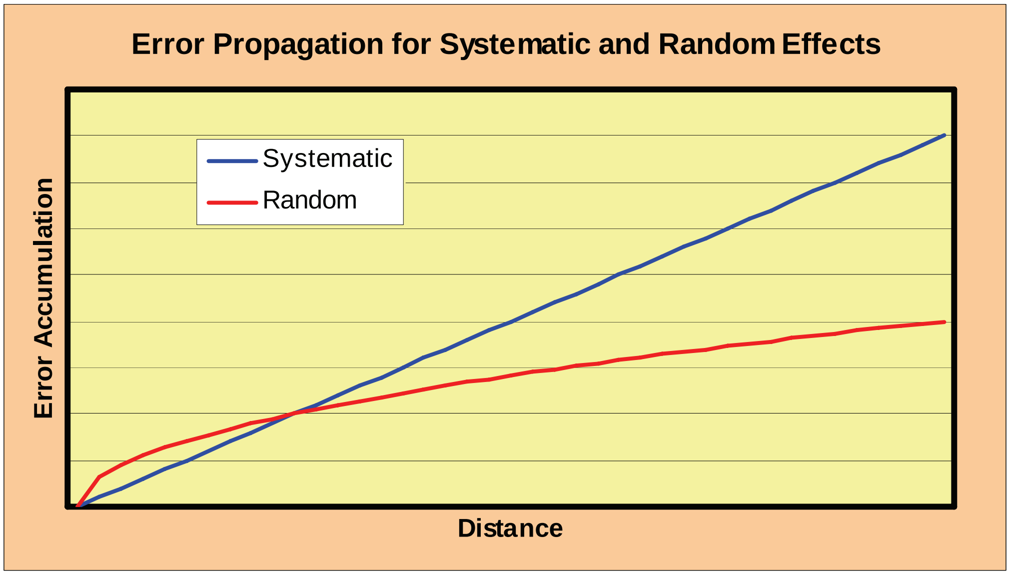

Figure 1: The propagation of systematic and random errors as a function of distance between survey monuments.

A similar system, utilizing the Poisson spot of light diffraction from opaque spheres, was proposed in 1990 by L. Griffith [9, 10] and his colleagues for the construction of an FEL at Lawrence Livermore Laboratory. It includes an elaborate feedback system to maintain the pointing direction of an expanded light beam and eliminates the need for inserting and removing reference targets as required in the SLAC design, as many spheres can occupy the cross section of the light beam. This system was designed to provide transverse positioning on the order of ±25 μm over a 300-m-long FEL.

Due to diffraction effects, the transverse sizes of the light beam expand over long distances. The refractive bending of the light beam in air with temperature inhomogeneity makes it necessary to enclose the beam path in vacuum vessels. In practice, the above techniques establish SLR nearly a meter away from the main electron-beam axes, and the transfer error is not negligible, especially when the relative position of the accelerator component to the SLR may change in daily temperature variations.

In 2004, Shintake et al. made a step towards overcoming these difficulties by proposing an on-axis alignment procedure using a laser beam and an Airy diffraction pattern for the SCSS x-ray FEL project [11]. They plan to enlarge the optical aperture by opening the gap of in-vacuum undulators during the alignment. An iris is attached to the geometric center of each cavity beam position monitor (BPM). A laser beam is used to image the iris onto a CCD camera downstream to detect the transverse misalignment. The estimated transverse accuracy of positioning the geometric centers of the BPMs is on the order of several micrometers over the distance of 25 meters.

Recently, a natural extension to the above techniques was made when we proposed an x-ray photon-beam-based system using a dedicated x-ray source [12]. Two retractable pinholes at each end of the beamline define a reproducible x-ray beam axis (XBA). Target pinholes are precisely positioned on the XBA using pinhole camera techniques. Position-sensitive detectors responding to both x-ray and electron beams enable the direct transfer of the positions from the XBA to the electron beam. We estimated that the system can deliver an alignment accuracy in the micron range over 200 meters.

In this work, we will evaluate the major components of the photon-beam-based straight-line reference for accelerator alignment, and illustrate the advantages of x-ray-beam-based alignment.

2. MAJOR COMPONENTS OF THE PHOTON-BEAM-BASED STRAIGHT-LINE REFERENCE

In this section, we will discuss the basic building blocks of the straight-line references based on a light beam: the source, the beam, the target, and fiducialization of accelerator components. We will see that most instrument errors reduce as the wavelength shortens.

2.1. Photon beam sizes and compatibility with accelerator chamber

If we choose a cylindrical axis with the z-axis along the propagating beam axis and its origin located at the beam waist, then the intensity distribution of a simple, lowest- order Gaussian light beam [13] is given by

$$\left|E(r,z)\right|^2 = \frac{\sigma(0)^2}{\sigma(z)^2}\left|E(r,0)\right|^2 e^{-\frac{1}{2}\left(\frac{r}{\sigma(z)}\right)^2}, \tag{1}$$

where the rms beam radius σ is a function of the distance z and the Rayleigh length $z_R = \sigma_0{}^2 / \lambdabar$,

$$\sigma(z) = \sigma(0)\sqrt{1+\frac{z^2}{z_R{}^2}} = \sigma_0\sqrt{1+\frac{z^2}{z_R{}^2}}\,. \tag{2}$$

For visible light with a wavelength λ = 0.632 µm and a Rayleigh length of 100 m, the rms radius of the beam waist reaches $\sigma_0 = \sqrt{\lambdabar z_R} = 3.2\ \text{mm}$. The full beam size at a Rayleigh length away is about 10 σ_0, in the range of centimetres and could not be contained in an accelerator chamber. If we reduce the wavelength by a factor of 10^4 (λ = 0.063 nm, energy = 20 keV), the minimum rms radius is reduced to 32 µm, and the full beam is well within the confines of an accelerator chamber.

2.2. Light source and beam axis

The diffraction effect makes it necessary for a laser-beam-based alignment to use nearly parallel light beams to minimize the photon-beam divergence. Here the SLR is defined by the designated optical center of the camera detector and the direction of beam propagation (Figure 2). Any minute changes in the direction of propagation could result in a substantial position error at a location far away from the camera detector. For example, over a 200 m distance, a 10 nrad deviation results in 2 µm offset in beam axis position. It is thus necessary to stabilize the laser beam direction using feedback systems [9]. The longer the accelerator is, the higher the requirement on the beam stability.

Since the diffraction effect is proportional to the wavelength of the photons, x-ray beams with wavelength in the 0.02 – 5 nm region will remain in the small accelerator vacuum chamber even going through a small pinhole aperture (source pinhole in Fig. 3). If we use another retractable pinhole, referred to as detector pinhole in Fig. 3, to mark the center of the camera detector, the straight line linking the centers of these two pinholes will be taken as the definition of the x-ray beam axis (XBA) and is used as the SLR.

In practice, it is a much easier task to maintain the position stability of a pinhole to within 2 μm than to maintain the angular stability of a laser beam to 10 nrad, a mere 10 nm displacement of a 1-m-long support structure. In short, the x-ray beam axis is *passively stable*. The longer the accelerator is, the more pronounced the advantage.

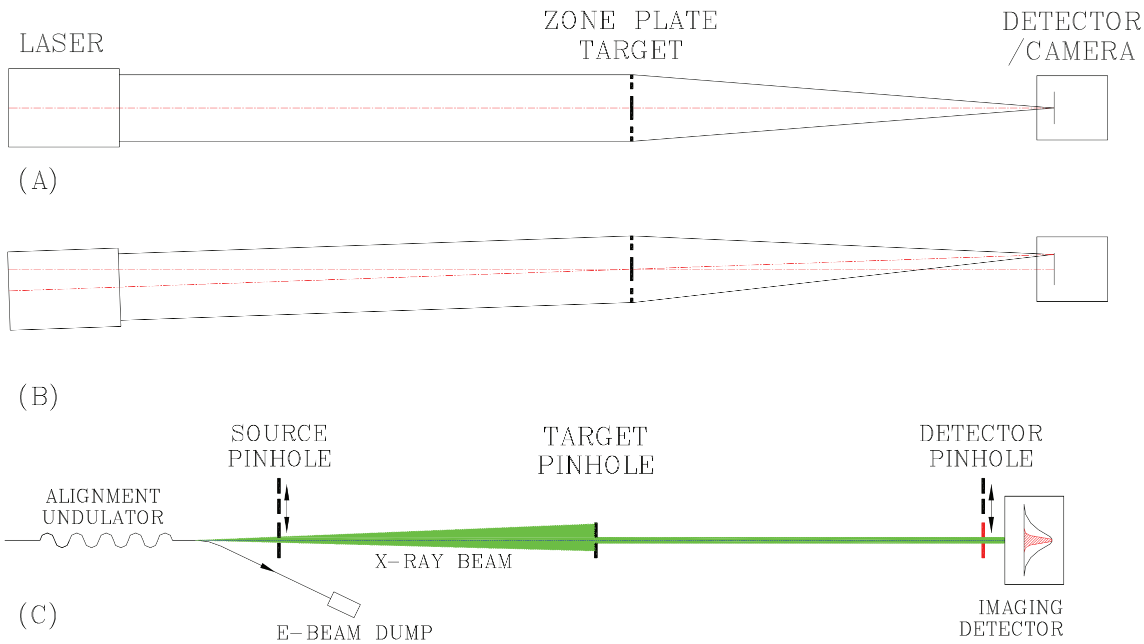

Figure 2: Definition of the optical axes: (A) parallel laser beam defines the axis with the optical center of the camera detector and the direction of the beam propagation. (B) When the laser beam tilts, the target position reading changes. (C) X-ray beam axis is defined by two pinholes (source and detector pinholes).

2.3. Alignment targets, position sensitivity and fiducialization

The large size of the laser beam has two effects on accelerator alignment: (1) The large beam makes it necessary to use targets centimeters in transverse dimensions, making it difficult to determine its optical center to micrometer accuracy. (2) Since a visible light beam cannot travel freely inside the undulator or accelerator vacuum chamber, one needs a separate alignment beam-transport line at an offset from the accelerator, often in the range of one meter. At these distances, transferring the positions of alignment targets to accelerator components at micrometer accuracy is difficult.

In the x-ray region, on the other hand, the pinhole targets will be less than 100 μm in diameter, and zone-plate targets will have concentric circles near 10 μm in width. Hence it is not difficult to fiducialize the centers of the targets with micrometer accuracy.

Finally, since x-ray beams through pinhole apertures have transverse sizes similar to that of the electron beams (σ_e = 10 – 100 μm), it is possible to use position-sensitive devices responding to both beams, such as wire scanners or fluorescent screens, to directly transfer the positions of the XBA to the electron trajectory. The electron beam, at the position coincidental to the x-ray beam, will be used to fiducialize the BPM and other beam line components.

3. ALIGNMENT PROCEDURES

In this section, we will illustrate the use of the x-ray-beam-based alignment (XBBA) with a proposed procedure for aligning the LCLS FEL. The LCLS undulator hall is 130 m long. An alignment undulator source may be positioned 30 – 40 m upstream of the first FEL undulator. The effective source is defined by a retractable tungsten pinhole 10 – 15 m upstream of the FEL. A scintillator detector / camera station will be installed ~ 30 m from the last FEL undulator along with a retractable pinhole for marking the optical center of the camera detector. The total beamline is 200 m long from the source pinhole to the camera detector.

3.1. X-ray source and beam setup

We use an undulator as an x-ray source since it supplies the required high-brilliance x-ray photon beam at low average electron beam current. The device uses the same magnetic structure as others in the undulator farm. We chose a 10.66 GeV electron energy to generate x-ray photons of 24.8 keV energy, or 0.5 Angstrom in wavelength.

The reference XBA is set up by conventional survey methods. The source and detector pinhole, both at inserted position, are positioned onto the design electron beam axis at the best achievable accuracy (Fig. 3A). Once the two pinholes are set, the primary coordinates are uniquely defined by the following rules. The *z*-axis or the XBA is the straight line linking the centers of the two pinholes, from the source to the detector. The *Oyz* plane is defined by the triangle formed by the center of the earth and the two pinholes. The *y*-axis is perpendicular to the *z*-axis, and pointing up, while the *x*-axis is defined by the *y* and the *z* axes via the right-hand rule. Due to ground motion and mechanical instability of the support structure and the insertion mechanism, this coordinate system will move relative to the tunnel and other components at later time. This will be discussed further in Section 4.

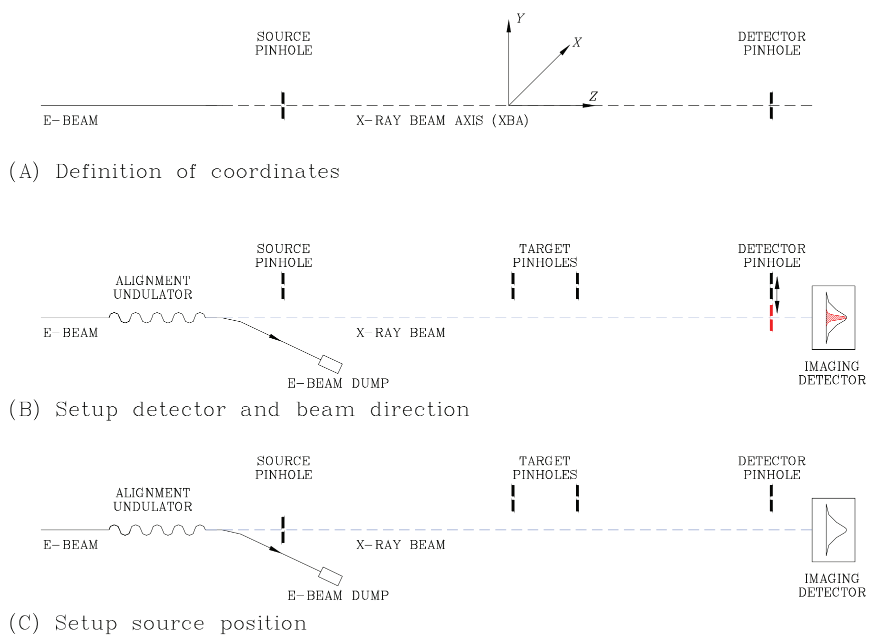

Figure 3: Setup procedures of x-ray beam axis: (A) Definition of the XBA coordinates, (B) setup detector with a retractable (detector) pinhole, and (C) setup x-ray undulator source position.

Next, we bring the alignment x-ray beam to the XBA. We use the detector pinhole to mark the optical center of the imaging detector. By iteratively centering the beam on the detector (Fig. 3B) and maximizing its flux through the source pinhole (Fig. 3C), we can bring the x-ray source point to the XBA and the x-ray beam parallel to the XBA.

3.2. Align pinholes to the x-ray beam axis

Pinhole targets can be aligned to the x-ray beam axis using the projected beam image on the camera detector (Fig. 4). The pinhole will be moved in the transverse direction until the beam image is optically centered on the camera. For nearly optimal pinhole dimensions, geometrical optics gives a good approximation. For an off-axis pinhole target, the offset and spot size on the detector increase nearly linearly with the distance between the target and the detector. Since we can determine the center of an image at a fraction (~ 10%) of its spot width, we estimate that the rms accuracy of the x-ray pinhole position is 2.5 μm over the 200-m-long undulator hall.

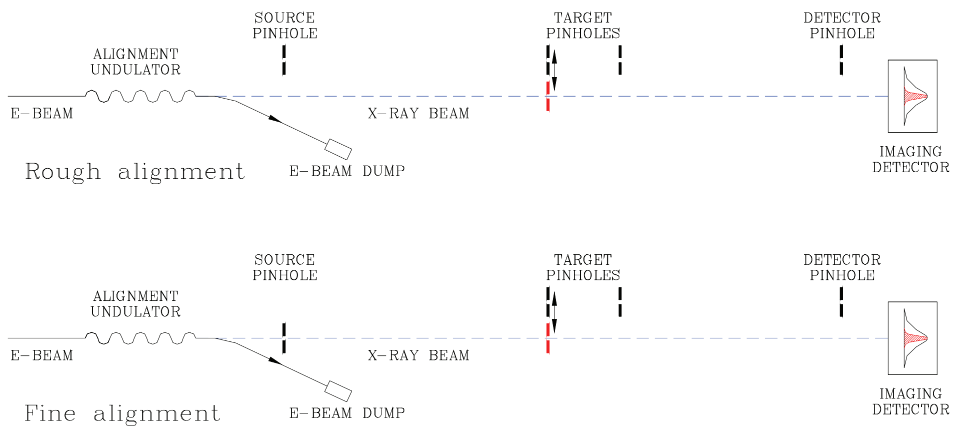

Figure 4: Schematics showing the alignment procedure of x-ray pinholes: rough alignment (upper panel) and fine alignment of pinholes (lower panel).

3.3. Detecting both x-ray and electron beams, fluorescent screens and wire scanners

Screens based on radiation-induced fluorescence respond to both x-ray photons and electrons, so the wire scanners, which work by partially blocking the beam. They are used mainly for measuring the transverse profiles of the particle beams. However, they can also be used, in some cases, for measuring the beam centroid. If we install a fluorescent screen downstream of an x-ray pinhole and use it to register the centroid of the x-ray beam passing through the pinhole, we are able to record the position of the XBA at that location. By subsequently bringing the electron beam to center on the same spot, we are able to transfer the position of the XBA to the electron beam at that location.

3.4. Fiducializing BPMs online and transferring x-ray beam positions to electron beams

If we install electron beam position monitors (BPM) in close proximity to a pinhole / screen combination, and bring the electron beam to coincide with the XBA at that point, the offset of the BPM can be directly determined (Figure 5). This BPM will be able to provide absolute transverse coordinates of the e-beam from now on.

3.5. Align other beamline components

Using a number of pinhole / screen combinations to provide multiple anchoring points along the accelerator, other BPMs and magnetic quadrupole centers can be determined using electron-beam-based alignment (EBBA) techniques. At an early design stage of the accelerator, it will be necessary to determine the minimum number of anchoring points in order to bring the overall alignment within physics specifications.

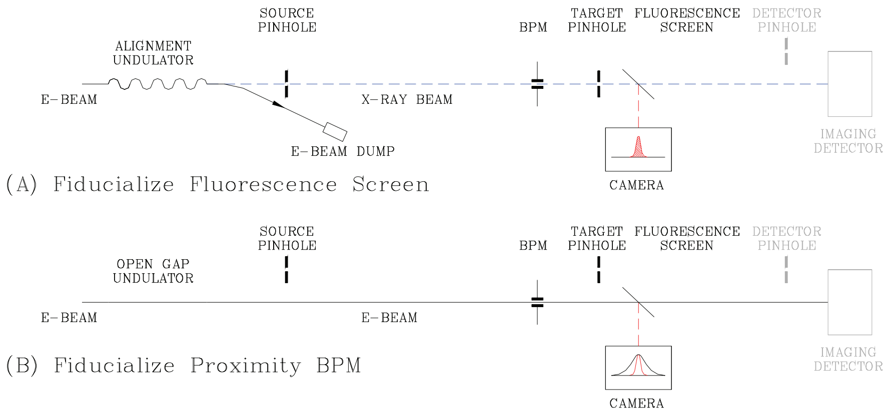

Figure 5: Fiducialization of an electron BPM.

4. FURTHER DISCUSSIONS

In this section, we discuss several technical issues related to the application of the x-ray beam-based-alignment technique.

4.1. Reproducibility of retractable monuments, targets, and screens

By definition, the two master monuments, the source and detector pinholes, are always on the *z*-axis. A typical set of measured positions of accelerator components may be plotted in Figure 6. The error bar of each target point not only includes the uncertainties of the x-ray measurements but also includes the mechanical irreproducibility of the target insertion mechanism. If the positions of the monuments relative to the accelerator components change for any reason (temperature gradient, earth’s tidal motion, or simply exercising the pinhole mount actuators), the coordinate system would change. As a result, the error bars of the measure position will further increase. Such errors could be minimized by not moving monuments until an entire set of measurements is completed. In a complex accelerator environment, however, interruptions are common due to machine conditions. It is important to design highly reproducible insertion mechanisms for x-ray targets and for the two monuments. We note that actuation mechanisms for inserting alignment targets and monuments have been developed and have demonstrated submicrometer repeatability [14].

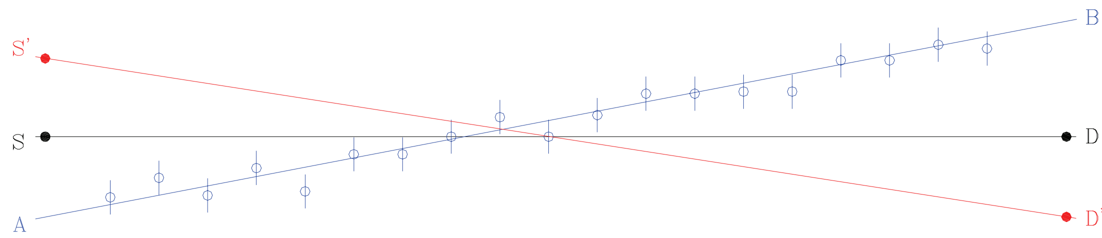

Figure 6: A typical set of position measurements in the x-ray beam system. The source pinhole (S) and the detector pinhole (D) define the z-axis. The RMS deviations from the regression line AB should be independent of the coordinate system change from DS to D'S'.

4.2. Real-time measurement and feedback

In long accelerators with stringent alignment tolerances, it is often required to measure the component position during beam operations and apply corrections in real time. Figure 7 shows a possible implementation using an off-axis x-ray alignment beamline. The electron beam is steered through a chicane or a two-stage trajectory offset before entering the main undulator hall. The offset of the two beams are adjustable from zero to a maximum of several millimeters. Each critical component will have two independently retractable pinhole targets, one on-axis and the other off-axis, in the monitor beamline. The monitor beamline is parallel to the EBA and has its own independently operated source and detector pinholes, as well as its own detector system. Any change in the position of the component will shift the pinhole camera image on the detector, providing real-time information on the component motion at a resolution of micrometers. The information allows position adjustments to be made while the accelerator is running.

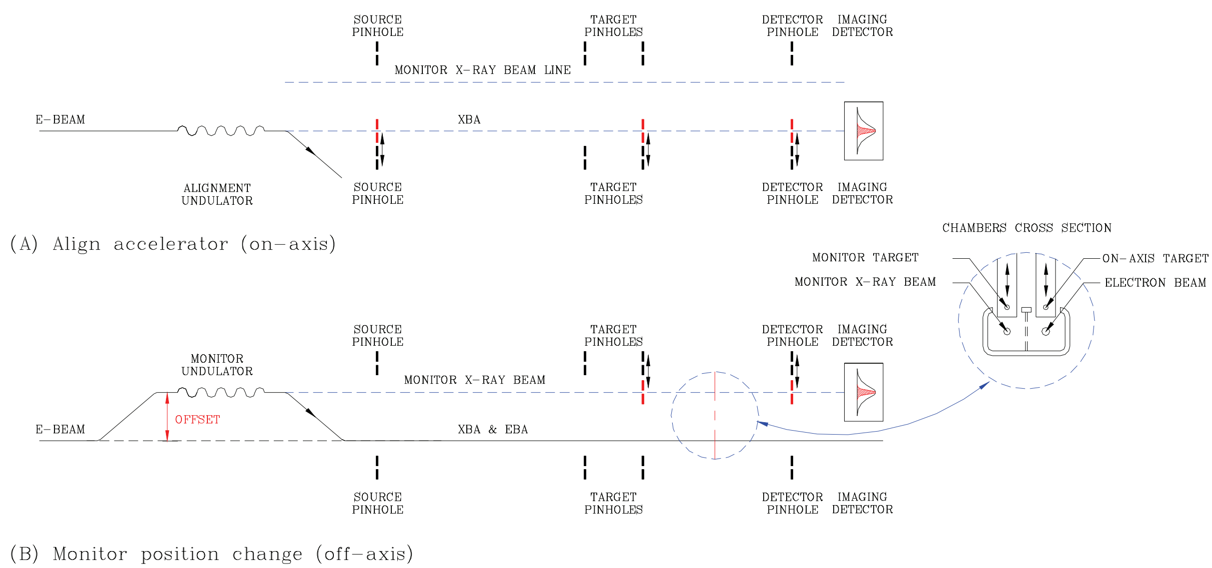

Figure 7: Real-time position monitoring system: (A) Alignment with on-axis trajectory and targets. (B) Observe position change with off-axis monitoring x-ray beamline. The inset shows two independently retractable pinhole targets, one used for XBA and the other for monitoring position changes. In x-ray FEL, the monitoring beamline has its own vacuum chamber to reduce the radiation background.

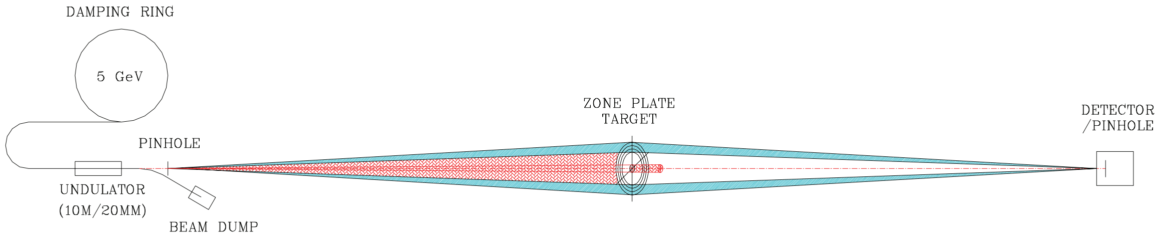

Figure 8: Schematic of a x-ray measurement based on zone plate targets for ILC main linac.

4.3. Zone plate targets and longer accelerators

Pinhole targets are useful for accelerators less than 500 m due to their simplicity. For long accelerators, such as the International Linear Collider (ILC) or the Compact Linac Collider (CLIC), x-ray zone-plate targets are needed. These targets will improve spatial resolution, as well as x-ray flux collection efficiency, with an improvement roughly proportional to the square root of the number of zones. Figure 8 shows how such a system can be used to align the ILC main linac or the final beam delivery system.

5. CONCLUSION

We have proposed a new alignment technique using an undulator x-ray beam produced by high-energy electrons. The proposal contains two major technical components: First, two solidly built x-ray pinholes (source and detector) are used to define a highly stable and reproducible x-ray beam axis (XBA). Second, the XBA is chosen to be collinear with the electron beam axis in order to minimize the transfer errors to accelerator components and maximize the coincidence between x-ray beam and e-beam.

A measurement accuracy of 1 – 3 μm can be achieved for target pinholes in the 200-m-long LCLS undulator hall. The accuracy can be further enhanced with x-ray zone-plate targets, especially in longer accelerators.

Acknowledgments

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