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

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Outline

- Introduction: Light beam as straight line reference (SLR), a little history
- Major attributes of light beam SLR (laser vs. x-ray)
- X-ray beam based alignment (XBBA) procedures, an example for LCLS undulator
- Further discussions
- Summary

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Introduction: using photon beam as a straight line reference (SLR)

- *More LINAC are being built since they deliver high-quality beams at high energies*
  - FELs: LCLS, DESY-XFEL, PAL/XFEL, Spring8-SCSS
  - Next generation linacs: ILC, CLIC
  - More and more stringent alignment requirements
- *The first step in their alignment is to establish a straight line reference (SLR)*
- It is difficult for conventional surveying techniques to break the barrier of 0.1 mm for distance of > 100 m
  - Takes many steps to establish reference system: Systematic and random errors build up with number of steps
  - References mounted in the tunnel drift with ground (ATL law)

➔ The SLR has to be established in a single step

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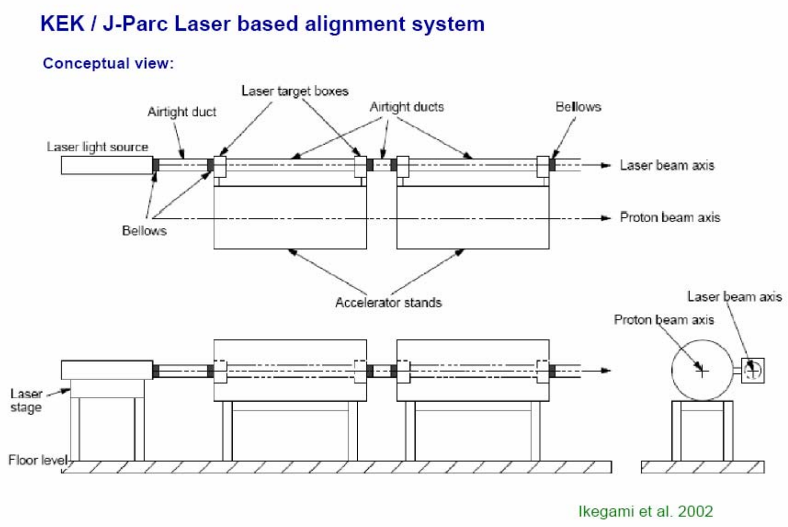
Previous work on light beam-based SLR: off axis

- **1968** W. Herrmannsfeldt constructed for SLAC linac
  - Fresnel lens imaging system, HeNe laser source
  - Resolving 25 μm displacement over a distance of 3-km
- **1990** L. Griffith (LLNL) proposed for FEL alignment
  - Poisson spot system, HeNe laser source
  - Estimated resolution 25 μm over a distance of 300 m



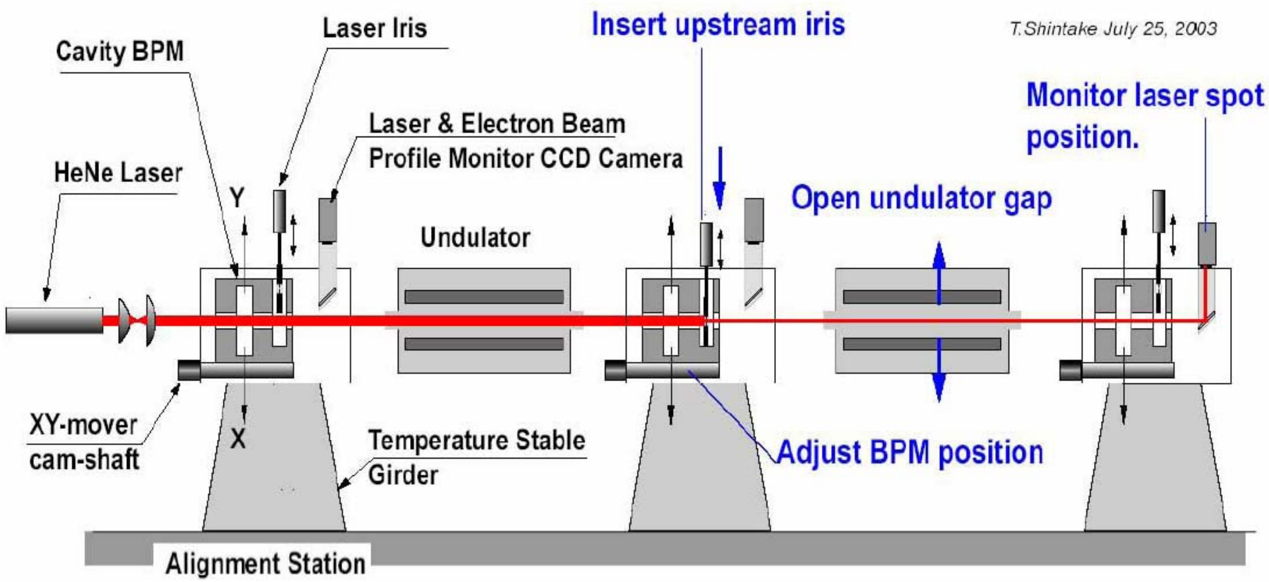
Common problems from the diffraction of laser beams:

- Beam larger than accelerator chamber → beamlines are off axis
- Targets are large
  - *Absolute fiducialization of targets difficult*
  - *Relative (displacement) measurements*

Previous work on light beam-based SLR: on axis

- **2003** Shintake et al. proposed for SCSS FEL alignment
  - Iris imaging system, HeNe laser source
  - several μm over a distance of 25 m

Short distance and large chamber. But it is the first on-axis light beam SLR for accelerators we know of. The concept could be further developed.

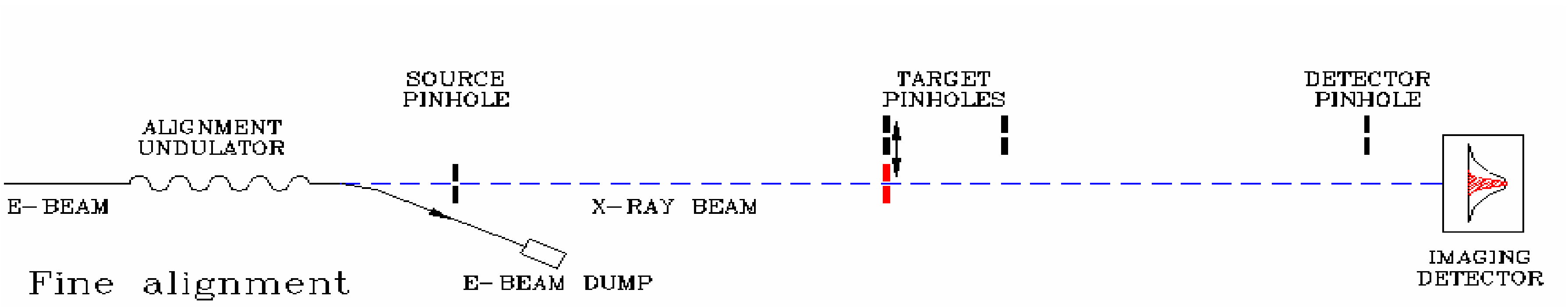


Photon beam as an SLR

X-ray beam-based SLR

- **2005** Yang and Friedsam proposed for LCLS FEL alignment
  - X-ray beam from undulator source
  - Retractable x-ray pinhole as monuments and targets
  - several μm over a distance of 200 m
  - A natural extension of previous work.

This talk will discuss its basic concept

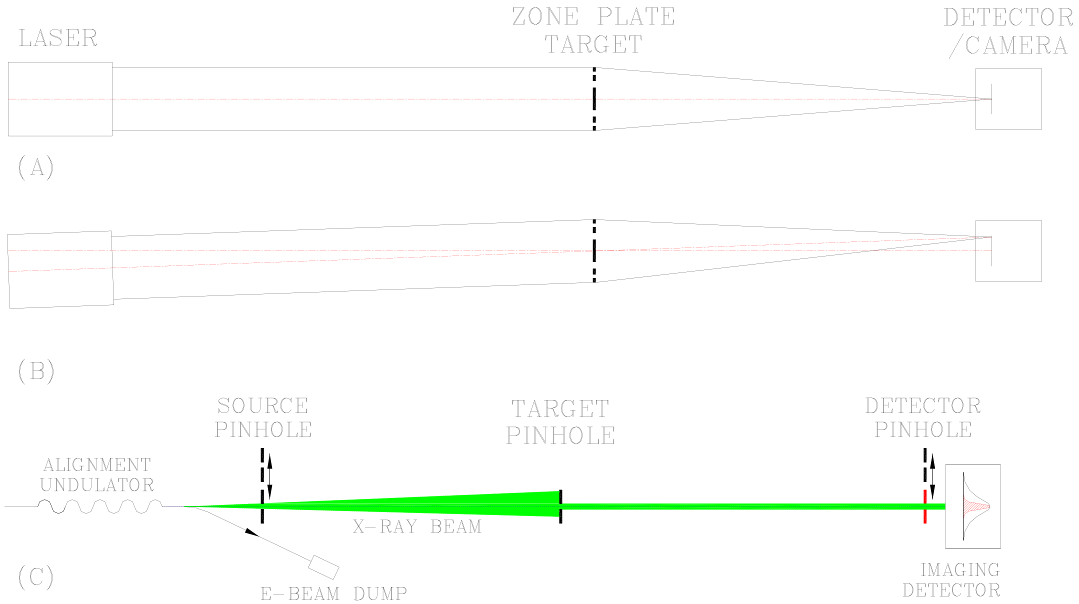


Major attributes of a photon beam SLR (laser beam vs. x-ray beam)

- **Size of the photon beam**
  - Diffraction effects determine aperture size.
  - Order of magnitude estimate: $R \sim (5-30)\sqrt{\lambda S}$
    - *Laser beam, 632 nm, 3 km, R ~ 2.5 – 15 cm*
    - *X-ray beam, 0.06 nm, 3 km, R ~ 0.25 – 1.5 mm*
- **Transfer fiducialization to accelerator components (magnets and electron BPM)**
  1. Determine the optical center of the target
     - *Laser: Define centers of mm and cm targets with μm accuracy is hard*
     - *X-ray: Pinhole size ~ 100 μm, zone plate ring width ~ 10 μm*
  2. Transfer target position to accelerator components
     - *Laser: Off-axis. Transfer with μm accuracy is hard*
     - *X-ray: On-axis, direct transfer of x-ray beam position to e-beam*

Major attributes of light beam SLR

Define and maintain a stable beam axis



Laser beam:
Need feedback system to stabilize beam direction

X-ray beam:
Passively stable

- **Parallel beam defines the SLR with a point and a direction**
  - Optical center of the camera detector
  - Direction of the parallel beam
- **Divergent beam defines the SLR axis with two points:**
  - Optical center of the camera detector (marked by **detector pinhole**)
  - Center of the **source pinhole**

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Alignment setups and procedures: Example of LCLS undulator

Hardware List

- An **alignment undulator**, 20 – 40 m upstream the main undulator
- One pinhole to define the source (**source pinhole**), 10 – 20 m upstream of the main undulator, retractable and highly reproducible.
- One pinhole at the end of the beamline to define detector center (**detector pinhole**), retractable, and highly reproducible. Distance to source: **200 m**.
- One pinhole (**target pinhole**) in every long break, remotely adjustable in X-Y direction, with micron accuracy.
- fluorescent screen (or good wire scanner) at every electron BPM.

Steps of the Alignment Procedure

1. Set up x-ray beam axis (XBA)
2. Align the source undulator and fiducialize the detector to the XBA
3. Align x-ray pinhole targets to the XBA
4. Align / fiducialize beamline components to the XBA

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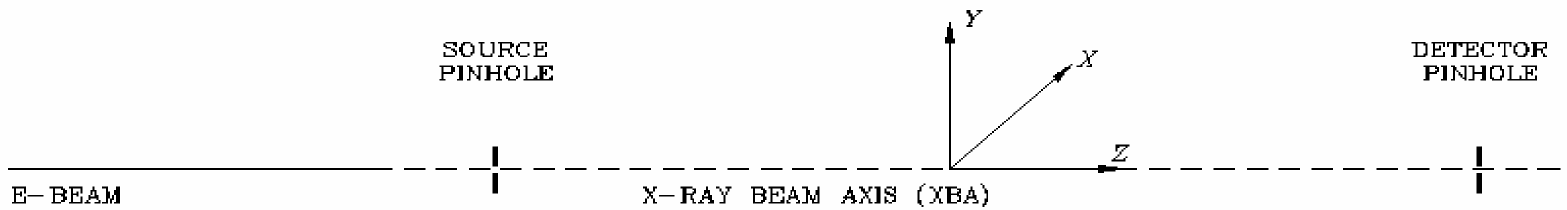
Alignment procedures

1. Set up X-ray Beam Axis (XBA)

- Position **source pinhole** and **detector pinhole** using the survey network. The survey network becomes a secondary coordinate system afterwards.
- The primary coordinate system is given as follows,
  - *z*-axis is from center of source pinhole to center of detector pinhole (SLR).
  - *Oyz* plane goes through the center of earth, *y*-axis up and perpendicular to *z*.
  - *x*-axis horizontal, *Oxyz* forms a right-hand triad.
- Source and detector pinholes are retracted during accelerator operation
  - Micrometer reproducibility is needed.
  - Angle tolerances are less stringent than those for the laser and mirrors.
  - XBA or accelerator will move as the tunnel deforms (ATL law).



(A) Definition of coordinates

Alignment procedures

2. Fiducialize the detector and align the x-ray source to the XBA

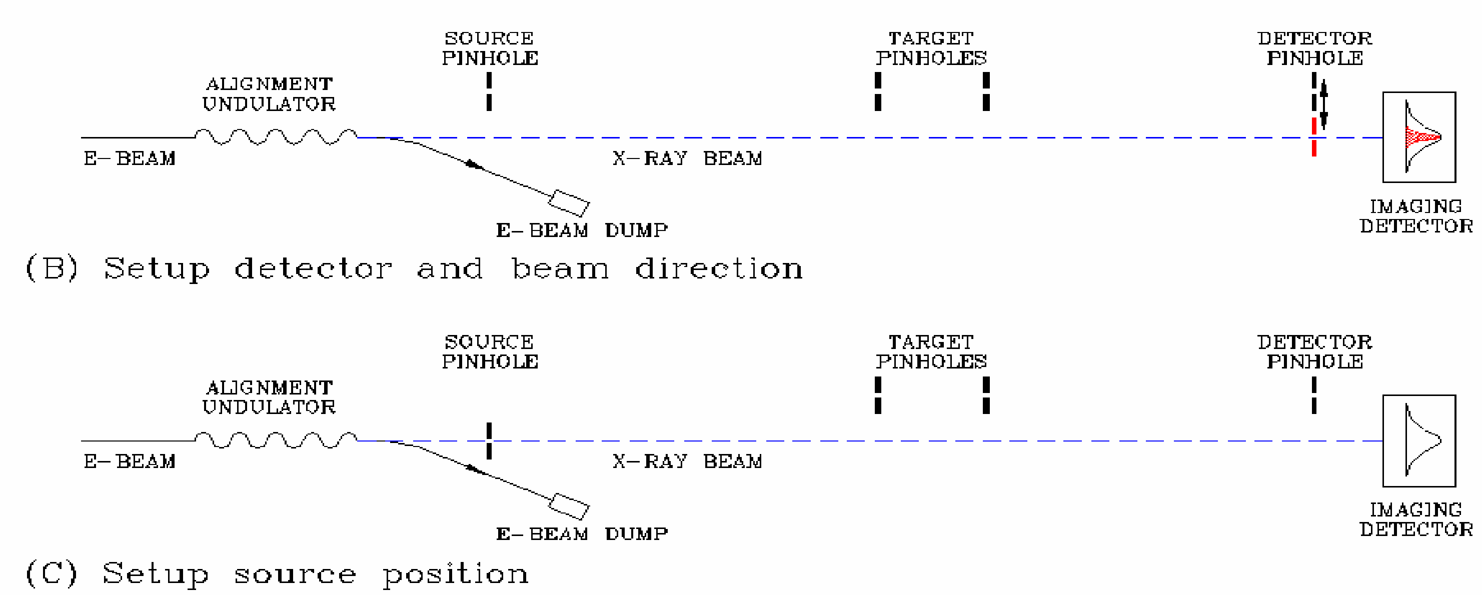
- **Fiducialize the camera detector optical center**

  Insert detector pinhole, the center of the beam spot is on XBA.

- **Align the undulator source to the XBA**

  Insert source pinhole. Center of the beam spot on the detector.

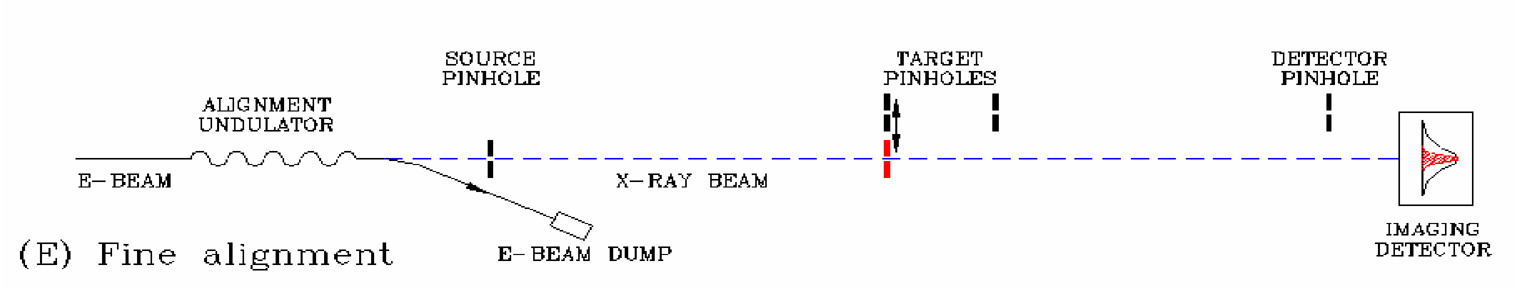
Maximize the flux by iterating these steps. These steps are important for improving alignment **efficiency** but not very important for alignment **accuracy**



Alignment procedures

3. *Align target pinholes to the XBA*

- Insert the source pinhole: stable source location. Electron beam motion will only cause x-ray beam intensity fluctuations
- Insert target pinholes one at a time and move it to center the x-ray beam spot on the detector plane.



- Alignment accuracy (Fresnel diffraction calculation ~ x-ray pinhole camera)

$$\delta_{align} = \eta \frac{\sqrt{\lambda S}}{4} g(z)$$

- In the LCLS undulator λ = 0.05 *nm*, *S* = 200 *m, η* ~ 0.1, *g(z)* < 1.

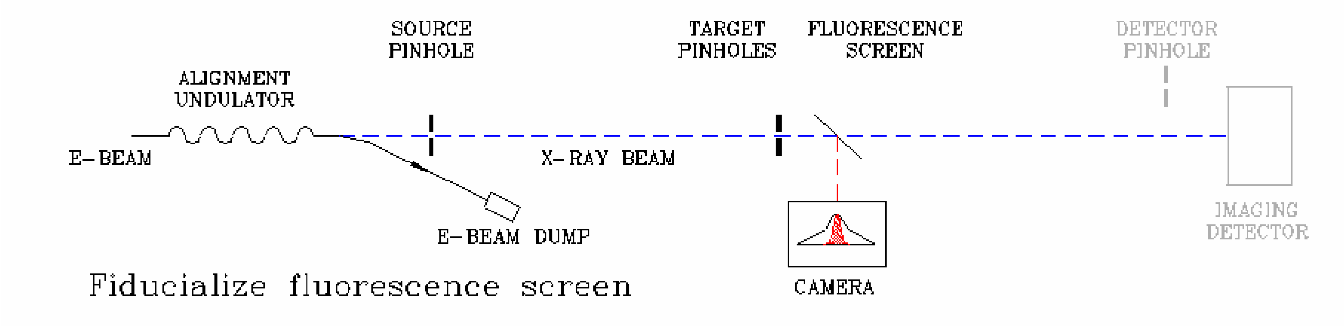
$$\delta_{align} \sim \pm 2.5\ \mu m$$

Alignment procedures

4. Align Undulator Components to the XBA

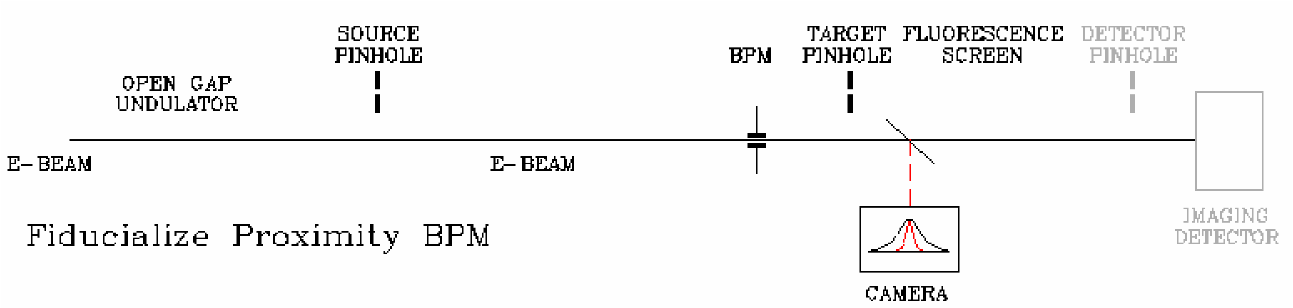
(A) Fiducialize a fluorescent screen downstream of a pinhole

Insert a fluorescent screen immediately downstream of a target pinhole. Take the center of the beam spot as the point where the XBA intercepts the screen



(B) Fiducialization of an electron BPM

Use the corrector magnets to move the electron beam spot to coincide with the x-ray spot on the screen. The reading on the BPM is the offset from the XBA.



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Summary of the estimated alignment errors for LCLS undulator components

(* Reference: B. Yang and H. Friedsam, Phys. Rev. STAB, March 2006)

Component	Transfer error	alignment accuracy	Notes
Target pinhole	N/A	2.5 µm	$\eta_x = 0.1$, $a = 30$ µm, $a_0 = 30$ µm, and $a_D = 30$ µm
Wire scanner	2.0 µm	3.2 µm + mech.*	$R = 15$ µm, $\eta = 0.1$
Fluorescence screen	2.0 µm	3.2 µm + mech.*	$\sigma_{res,x} = 10$ µm, $\eta = 0.1$
BPM	3.8 µm	4.5 µm	$\sigma_{res,e} = 40$ µm, $\sigma_e = 45$ µm, $\sigma_{BPM} = 1$ µm, $\eta_e = 0.05$
OTR screen	6.0 µm	6.5 µm + mech.*	$\sigma_{res,OTR} = 10$ µm, $\sigma_e = 45$ µm, $\eta = 0.1$
Quadrupole magnet	< 5 µm	< 7 µm	$E = 13.6$ GeV, $Q_0 = 3$ T, $\beta = 10$ m, $\varepsilon_Q = 0.35$
Undulator	~ 10 µm	~ 10 µm	Field error dependent, vertical only.

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Further discussions of technical issues

1. Reproducibility of target / monument insertion mechanism
2. Improving accuracy and efficiency with zone plate targets
3. Real-time measurements and position feedback

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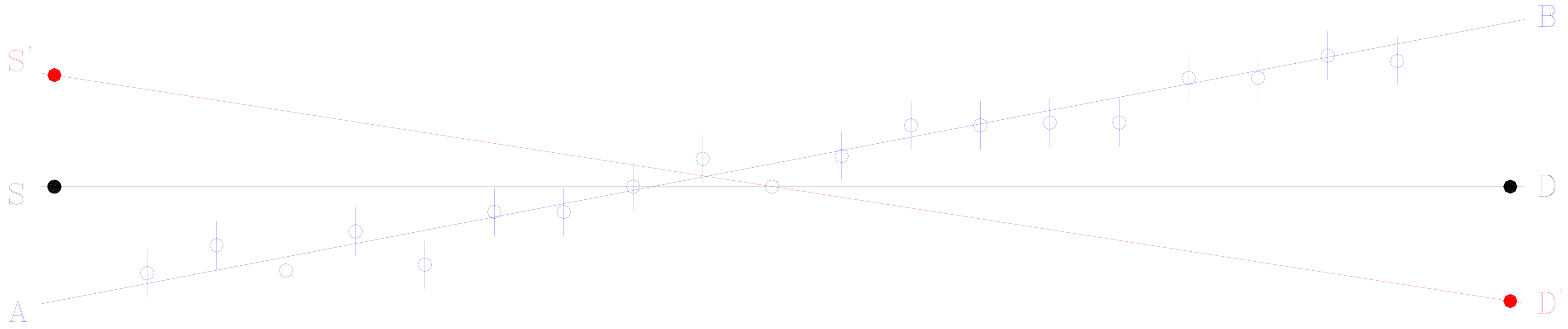
1. Reproducibility of target / monument insertion mechanism

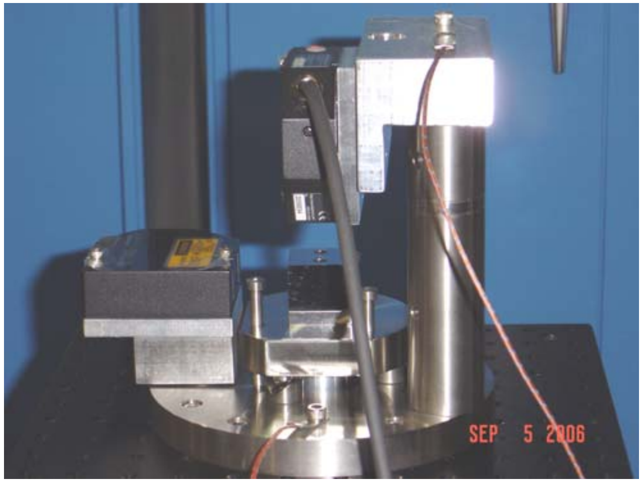
- Poor reproducibility of a **target** insertion mechanism contributes directly to the error bar for measurement of the attached component
- Poor reproducibility of **monument** insertion mechanism contributes to the error bar for all measured position

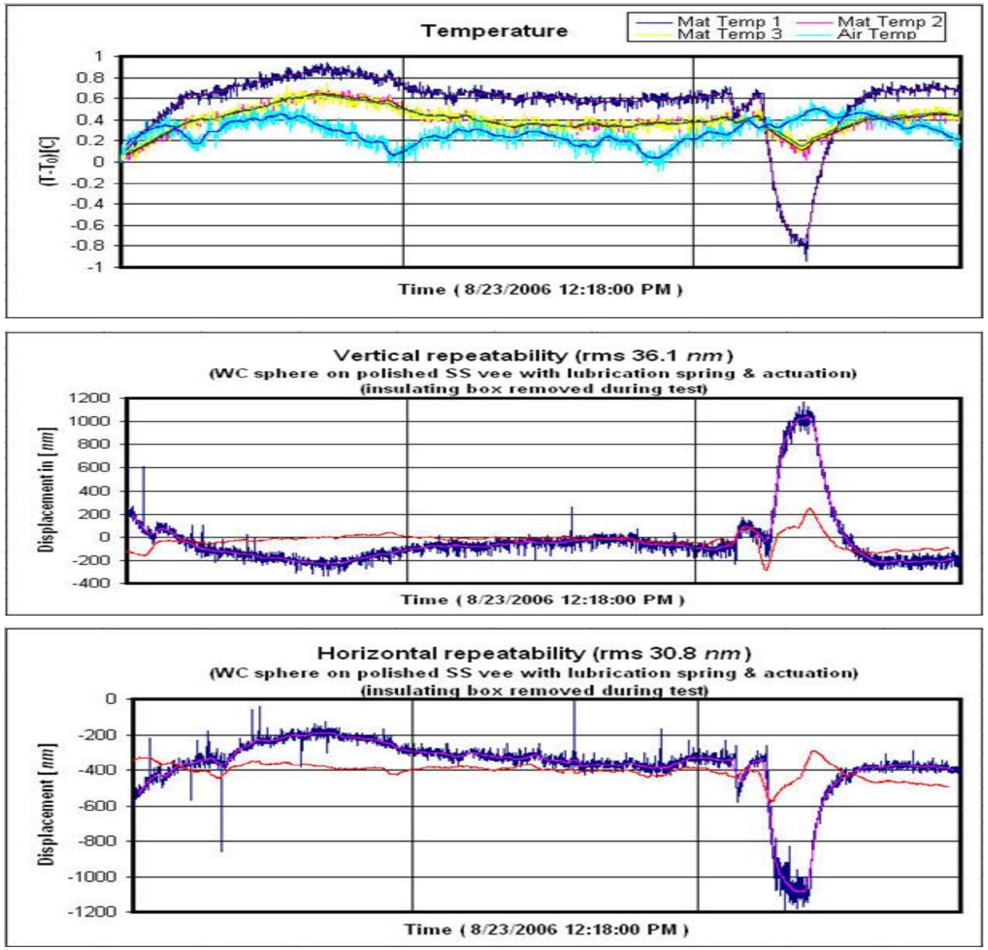
Micrometer reproducibility is required for all target and monument actuators

Slow position drifts due to temperature gradient and/or ground motion need to be corrected in real time through feedback



Reproducibility tests of target / monument insertion mechanisms





H. Friedsam and B. Yang, poster

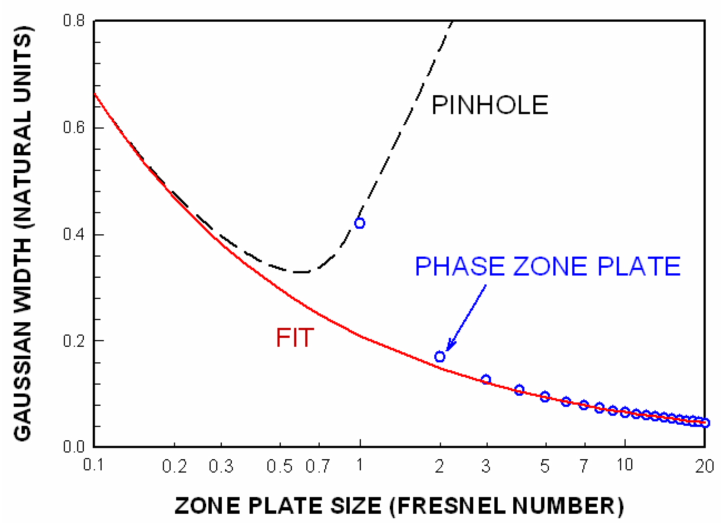
[Main Conclusions]

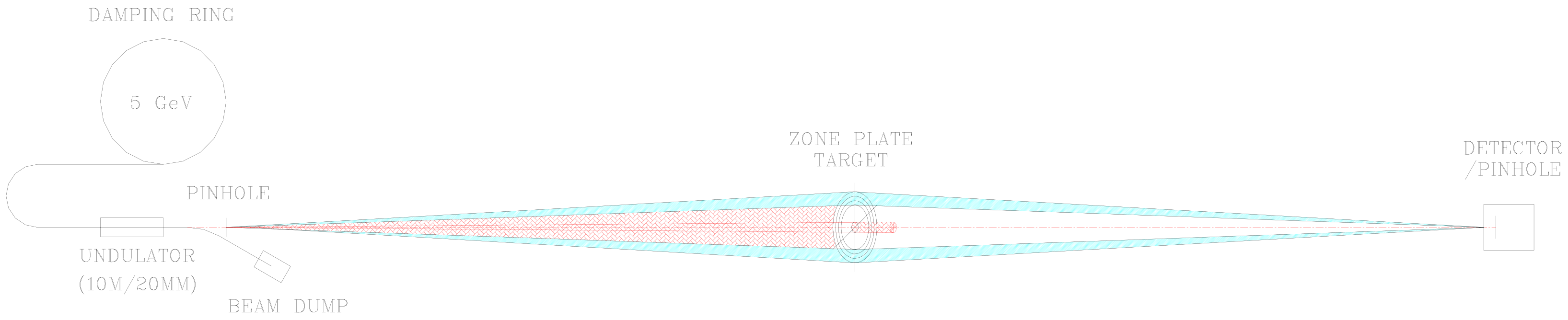
1. Sub-micrometer reproducibility of target / monument insertion mechanism may be obtained with properly designed kinematic mounts.
2. Temperature effects dominate position change

Further discussions

2. Improving positioning accuracy and optical efficiency with zone plate targets

- Fresnel zone plates improve positioning accuracy to **~10 μm over 10–20 km**. A phase zone plate with a handful of zones (≥ 4) can improve the resolution over the optimal pinhole by more than a factor of three.
- Flux efficiency increase ~ proportionally with zone plate area





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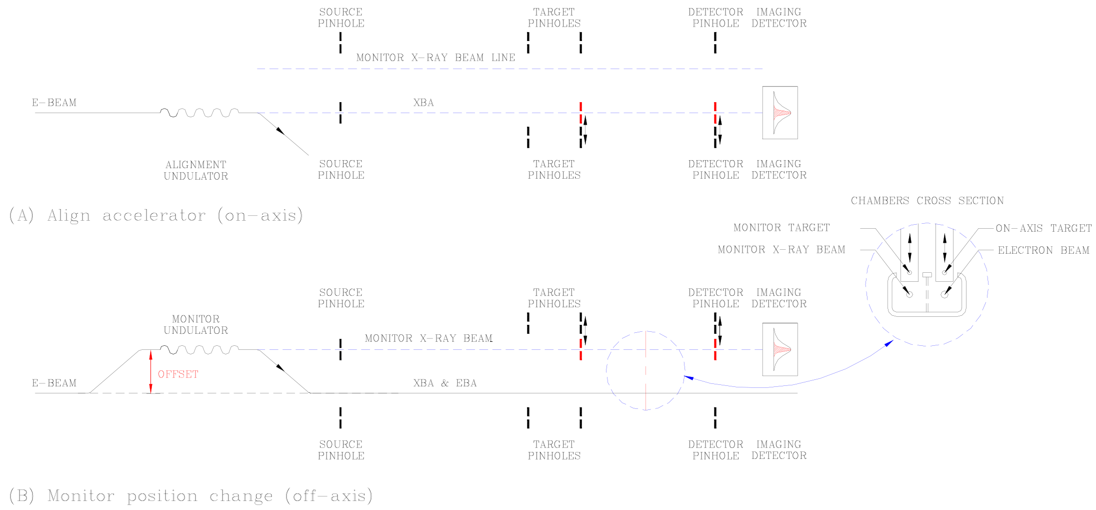
Further discussions
3. Component position monitor and feedback

- Periodic / daily observation of component positions for undulator / linacs
  - Tidal motion of the ground (phase of the moon / sun)
  - Settlement and diffusive motion of the tunnel (“ATL Law”)
- Real-time position monitoring system: “*X-ray wire monitor*”



- Zone plates should be used
  - Better resolution of undulator components position change (< 10 micron / 20 km)
  - Better use of x-ray beam flux (10x – 100x efficiency and measurement speed)

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Summary

- Laser beam based SLR has been the workhorse for many reasons
  - Good quality source / beam available since 1960's
  - Three decades of cumulated development and experience
  - Still most affordable for **relative** position accuracy ~ 25 μm in 3 km
  - Reaching limits at higher accuracies, or for absolute measurement
- X-ray beam based SLR is a natural extension
  - Short wavelength improves accuracy
  - Direct fiducialization of electron beam position reduces error
  - Good quality x-ray radiation source / beam are available recently (1990's)
  - Optical technology are available from synchrotron radiation community
  - Many engineering solutions need to be developed before practical use
  - It is complementary to survey techniques since it requires a high precision pre-alignment in the first place.

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