STRAIGHT LINE REFERENCE SYSTEM (SLRS) FOR THE ADJUSTMENT OF THE X-RAY FREE-ELECTRON LASER (XFEL) AT DESY

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ABSTRACT

In 2008, DESY will start the construction of the XFEL, with a total length of 3.3km. A high-precision alignment system based on an optical reference line is used to adjust parts of the XFEL beamline. For the undulator sections and photon beam lines several Straight Line Reference Systems (SLRS) from 150m up to 1000m in length will be needed. To eliminate atmospheric disturbance in the SLRS a vacuum pipe with a diameter of 300mm is provided. The estimated accuracy of the alignment system perpendicular to the beam axis is in the micrometer range. The current status of the development process is shown; both in simulation and experiments.

1 INTRODUCTION

The construction phase of the European joint project "X-Ray Free Electron Laser" will commence in 2008. Tolerances for the machine alignment are geared to the different parts of the facility. The tolerance for the alignment of the linac components is +/- 0.3mm with respect to 150m in length, the tolerance for the undulators and the photon beam line components is +/- 0.5mm with respect to 1000m in length, altogether valid in the two directions perpendicular to the beam. With conventional optical survey methods it is impossible to fulfil this requirement. For this reason a Straight Line Reference System (SLRS) is presently being developed and arranged. There are several individual systems necessary for the XFEL. Up to five SLRS beam tubes with lengths from 150m to 1000m are planned, as shown in figure 1. The SLRS will be operated in a vacuum pipe with a diameter of 300mm because of atmospheric disturbances.

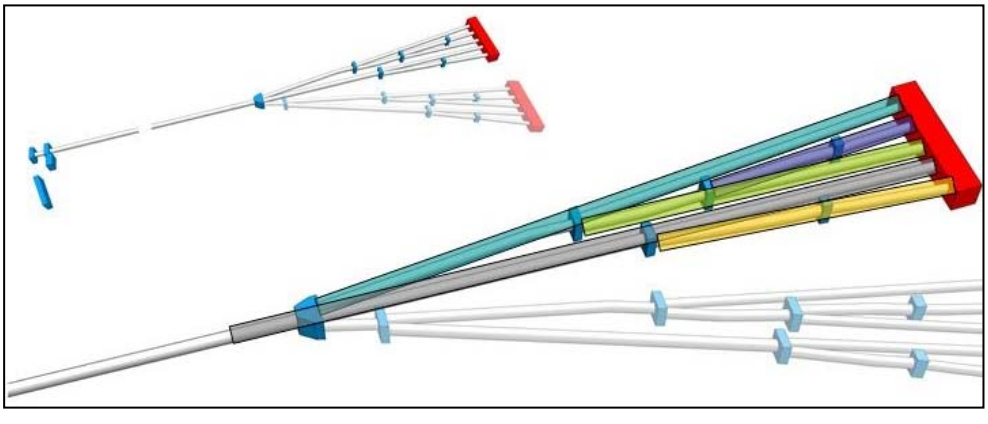

Figure 1: Planned installation of SLR-Systems in the XFEL tunnel

2 SLRS BASIC PRINCIPLE

There are two types of SLRS with different target types which are currently being evaluated. Both use a He-Ne laser with a wavelength of 633 nm as a light source. The Poisson Alignment system uses the diffraction patterns of spheres, the Active Light Source system uses single mode fiber ends as a target. The optical reference line is either defined by one selected ball and the center spot of its diffraction pattern at a CCD-Chip or by the center of a 5µm fiber and the center of its image at the CCD-Chip.

3 POISSON ALIGNMENT SYSTEM

3. 1 Background

Griffith [1] and Friedsam et al. [2] have already reported fundamental results of analysis and experiments concerning the subject of the Poisson Alignment System. In general, the size and quality of the Poisson Spot depends on the diameter of the sphere or the slice and their respective distance to the detector (see figure 2).

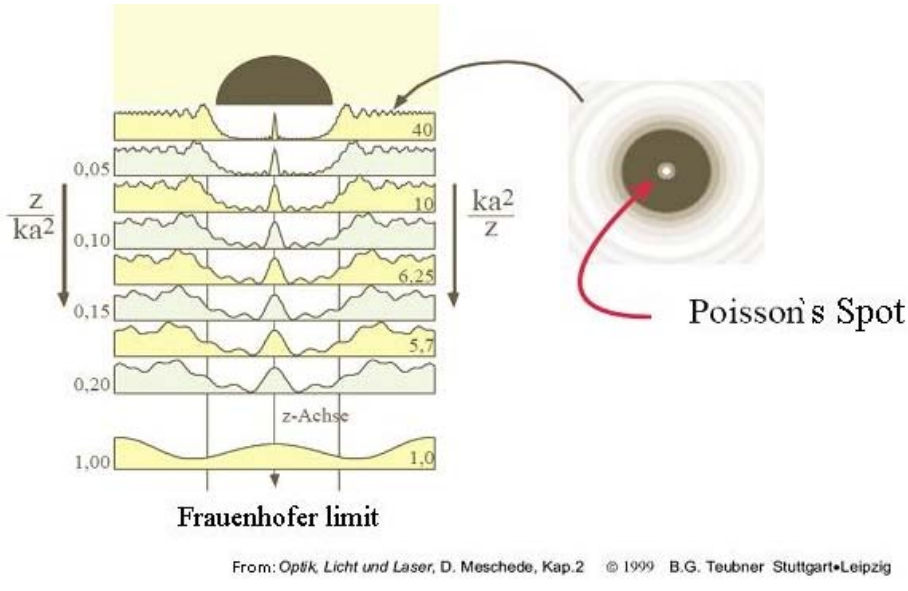

Figure 2: Dependence of the Poisson Spot on the distance to the detector

The shorter the distance to the detector the lower the spot diameter will be. The phenomenon of the Poisson Spot can be explained by the wave-particle duality of light. A more detailed formula for calculating the size of the Poisson Spot is given in by equations (1) and (2). “We can construct the light field diffracted by a disc with Babinet's principle and the results from a circular aperture. It consists of just the difference between the non-diffracted field, in the most simple case a planar wave, and the complementary field, which originates from a circular aperture.” [3]

$$\mathcal{E}(r) = \mathcal{E}_S e^{ikz} \left(1 + i\, e^{i\kappa(r/a)^2/2}\, \kappa \int_0^1 e^{-i\kappa x^2/2} J_0(\kappa x r/a)\, x dx\right) \quad (1)$$

with:

$\mathcal{E}(r)$ = amplitude of the electric field

$\mathcal{E}_S e^{ikz}$ = planar wave front

$k = 2\pi/\lambda$ = wave vactor with λ as wave lenght

$\kappa = ka^2/z$ = wave frequenz with *a* the radius of the circular aperture and *z* the distance between circular aperture and detector

"The diffraction image at a circular obstacle consists of the superposition of a planar wave and a diffraction wave of the circular aperture."[3]

$$\mathcal{E}(r=0) = \mathcal{E}_S e^{ikz}(1 + 2i\sin(\kappa/4)e^{i\kappa/4}) \text{ and } I(r=0) = \frac{c\epsilon_0}{2}|\mathcal{E}_S|^2! \quad (2)$$

with:

$\mathcal{E}(r = 0)$ = amplitude of the electric field on the optical axis (r = 0)

I(r = 0) = intensity of the Poisson Spot on the optical axis

c = speed of light

ϵ_0 = dielectic in vacuum = 1

3. 2 ZEMAX Simulation

To obtain general information concerning the technical feasibility of the alignment system simulations using ZEMAX (software for the design and optimization of optical systems,) have been performed. Simulations for the SLRS were performed using pipe lengths of 150m, 300m and 1000m. A Gaussian beam profile with λ=633nm and a Full-Width Half-Maximum (FWHM) of 100mm was used to calculate the diffraction patterns. During the first simulations no optics for laser beam expansion or for focusing has been included.

In order to acquire information about the scale and a possible rotation every machine component will get equipped with two spheres within a fixed distance. The interspace between these two spheres will be precisely calibrated.

The figures 3(a) and 3(b) show the results of the simulation for eight spheres with diameters from 10mm up to 30mm positioned at various distances within a 150m long system. In detail the diameters and positions have been: 30mm spheres at 145 and 105m distance, 23mm spheres at 45m distance and 10mm spheres at 5m distance between target and the detector.

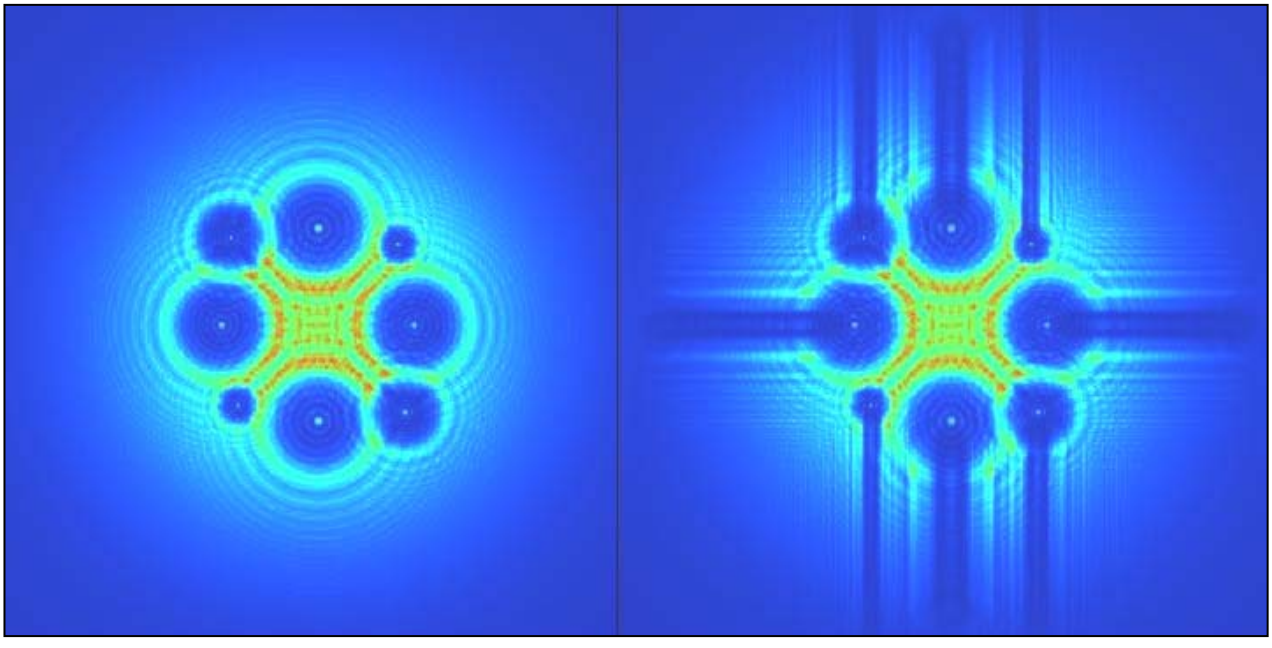

Figure 3 (a): ZEMAX simulation with 8 spheres; (b): Simulation with 8 spheres and holders

This setup is the typical setup for crossing the shafts. Additional system lengths for the photon beam lines have been calculated. The results show the technical feasibility of the SLR-System over 1000 metres in length.

3. 3 Empirical tests and results

For the first set of empirical tests, a Class IIIa 633nm He-Ne laser diode beam with coupled single mode fiber and a potentiometer adjustable output power of 3mW was used. The setup also included a fiber collimator with a collimated beam diameter of 10mm, a lens with d=120mm, f=100mm and an achromat with d=100mm, f=600mm. The apparatus served to expand the beam to produce a 100mm beam diameter as shown in figure 4. For the image capturing we used a Sony XCD-C700 with a 1/2” CCD-Chip and a resolution of 1024x768 pixels.

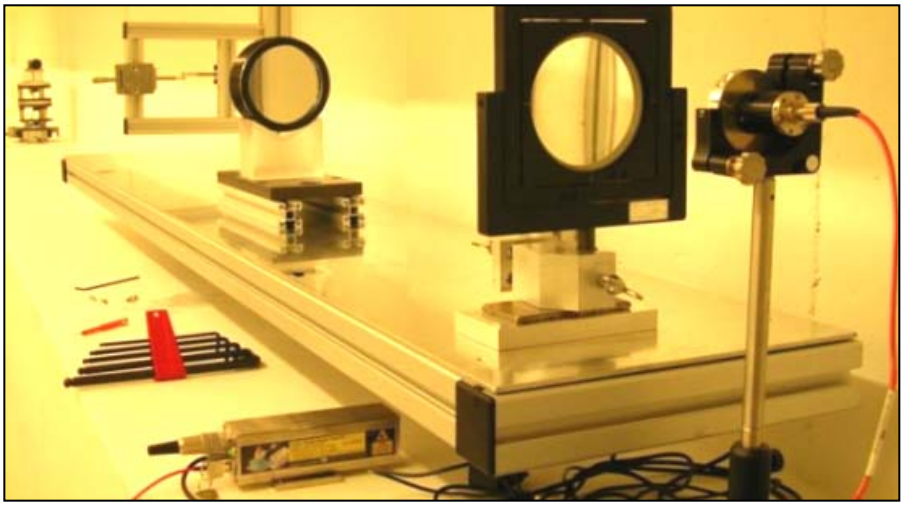

Figure 4: First setup for feasibility tests

In the first trial, four spheres with diameters of 10mm and 12mm were positioned at 23m and 41m in front of the camera. The entire length of the 100mm flared, collimated laser beam track was 55m. The image captured by the CCD-Chip is shown in figure 5. Of course it has been impossible to evaluate the translation of a sphere in the image sequences because of atmospheric disturbances, but the example gave a good impression of the image quality.

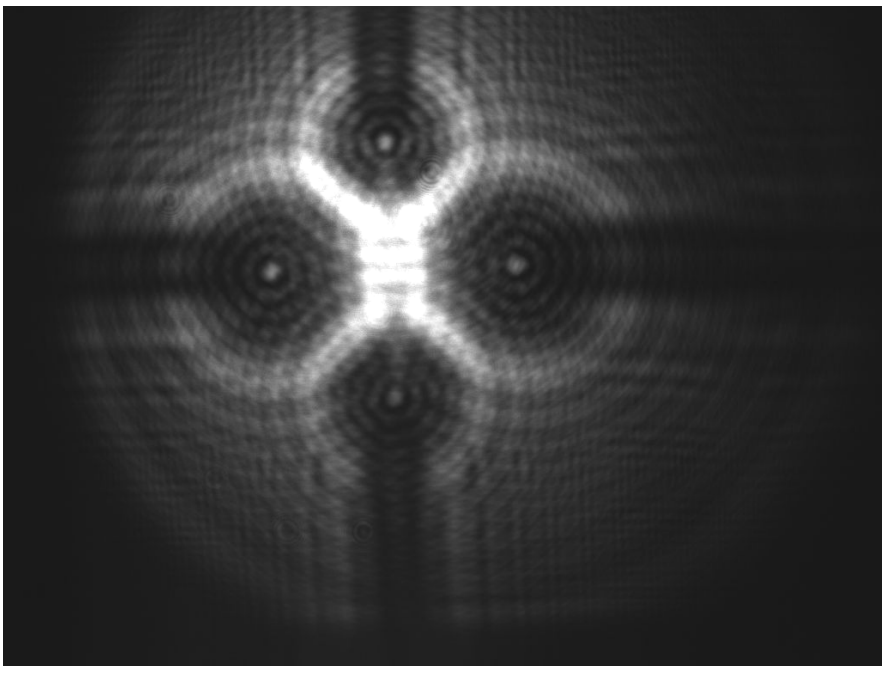

Figure 5: Image with four poisson spots on the 55m setup

Until the vaccum system will be installed, we use shorter tracks to check the image processing algorithms. The next track has been setup with a length of 5m overall, two spheres with 8mm diameter were positioned 3m in front of the camera. One sphere was mounted on a linear translation stage, shown in figure 6(a), with a micrometer screw for controlled translation perpendicular to the beam. Figure 6(b) shows one example image from the two Poisson Spots 3m in front of the camera.

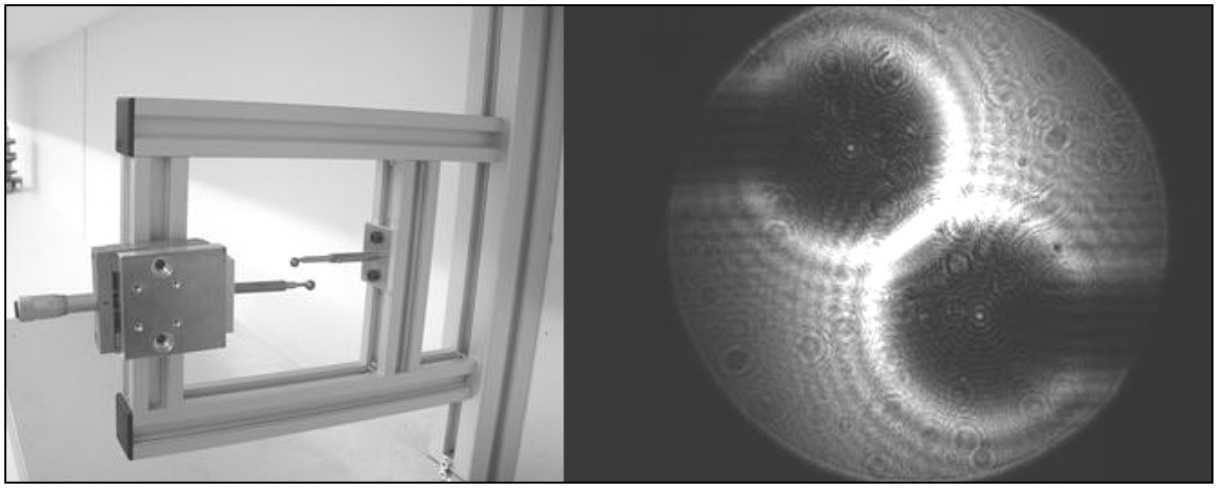

Figure 6 (a): Micrometer stage with mounted sphere; (b): image of two spheres with a diameter of 8mm

A couple of different methods have been used for image processing. One issue was to immediately start with ready-to-use free software (ImgageJ). At first a differential image between two consecutive images has been calculated. Figure 7(a) shows the result of this process. After a binary transformation (fig. 7b), edge operators (fig. 7c) and ellipse operators (fig. 7d) have been tested to calculate the distance between the two spots in the differential image.

A second method started with the detection of the centre of the Poisson Spots in the single images. Then the distances between the fixed spot and the moving spot were calculated from the image coordinates. The translation of a sphere can then be calculated by comparing the distances in the consecutive images. Both the edge operator and the ellipse operator did not yet reach the demands of accuracy we needed. We then switched to using an algorithm calculating the center of mass of the sinlge spots. The nominal translation of the moving sphere has been measured with a laser interferometer.

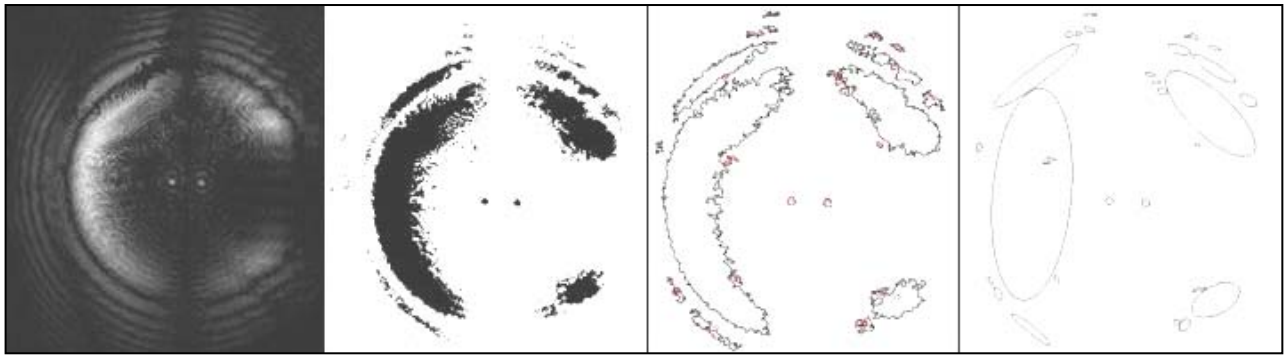

Figure 7 (a): Difference between two images; (b): Result of a binary transformation; (c): Result after using the edge operator; (d): Result after using the ellipse operator

The mean error between the nominal translation and the calculated distance was 12µm for the setup with 5m in length. On a different setup with a length of 1.7m the mean error of translation detection has been 17µm. A range of translations from 0.20mm up to 2.00mm have been measured in multiple epochs.

3. 4 Potential nonconformities

The aim is to develop the SLR-System to be as simple as possible and therefore be as unsusceptible to error as possible. To generate the Poisson Spot a round, thin and opaque slice in the collimated beam is equivalent to an opaque sphere.

The coherence length of the laser defines the maximum possible path difference for the development of the interference pattern. By using a slice the maximum acceptable tilting where interference is still possible is defined through the coherence length of the laser. Using a sphere is more productive as it is insensitive to tilt angles.

A tilt of the sphere around an axis perpendicular to the beam direction gives a cosine-error and influences the position of the Poisson Spot of the CCD-Chip. It can be calculated by observing a pair of spheres for every machine component.

The several optics such as lenses and achromats in the collimated beam path produced back-reflections, which impaired the quality of the beam. These kinds of errors depend on the coherence length of the utilised laser. A laser with very short coherence lengths e.g. 300µm minimizes these effects.

3. 5 Differences to former Poisson-Alignment-Systems

The Poisson-Alignment-System conceptualized by Griffith [1] used a quad cell position detector to detect the maximum of the Poisson Spot. Based on the advanced technology today it is possible to use a CCD-Chip as detector. This development gives the possibility to analyse interference patterns and Poisson Spots using image processing software. The center of the Poisson Spot can be calculated with sub pixel accuracy by using cross correlation algorithms (Prenting [4]).

4 DIRECT LIGHT SOURCE SYSTEM

4. 1 Basic principle

The direct light source system is based on fiber optics as an active light source, as shown in figure 8. The light source for the fibers is a laser coupled to a fiber optical beam splitter. A convex lens and a CCD-Chip are use to capture the image from the spots.

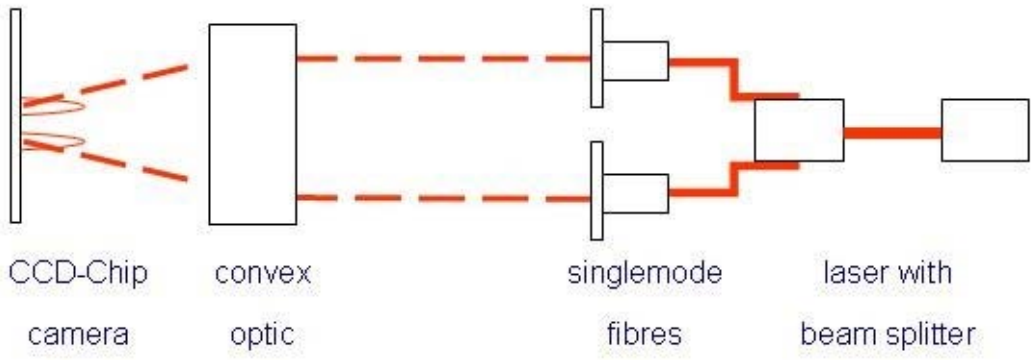

Figure 8: Basic concept of the direct light source system

4. 2 Equipment

For the first studies we used a low noise laser diode beam source: the 51FCM from Schäfter+Kirchhoff which is internally RF-modulated with a frequency of 0.4 GHz, shown in figure 9(a). This laser has a short coherence length of 300µm with λ=641.4nm and an adjustable output power of 5mW. The laser beam is coupled into a single mode fiber.

Furthermore a fiber optical beam splitter with four laser attenuators (SuK 48AT) to give precise laser output power reduction for each single mode fiber connector is used, shown in figure 9(a). To mount the single mode fiber optics we used FC-APC adapters, shown in figure 9(b).

The image capturing was done by using a convex lens and a CCD-Chip camera, shown in figure 9(c).

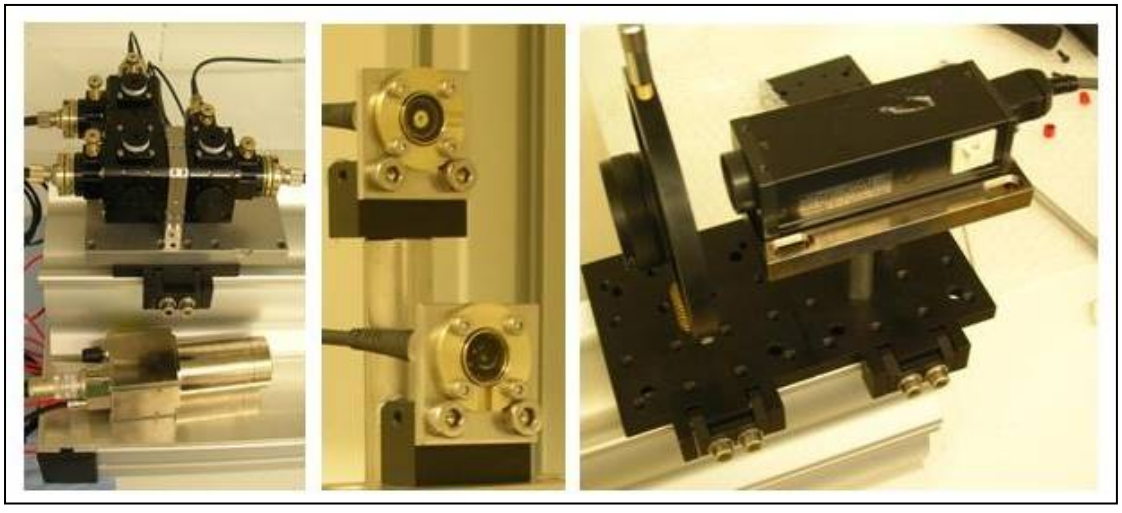

Figure 9 (a): 51FCM laser with beam splitter; (b): Fiber Optics; (c): Convex lens with CCD-Chip camera

4. 3 Empirical tests and results

With two setups of 1.2m and 1.7m in length we tested the technical feasibility of the direct light source system in our straightness systems laboratory at DESY. Figure 10(a) shows the laser, the optical beam splitter and the fiber optics mounted on a carriage and a micrometer stage. The configuration of the fiber optics for one of these tests in front of the camera is shown in figure 10(b). For the controlled translation perpendicular to the beam, one fiber optic was mounted on a micrometer stage. The image processing was identical to that used for the Poisson-Alignment-System. After a binary transformation we used an ellipse operator to calculate the centre of the spots in every single image. Finally we calculated the distance of translation using the coordinates of the spots in two consecutive images.

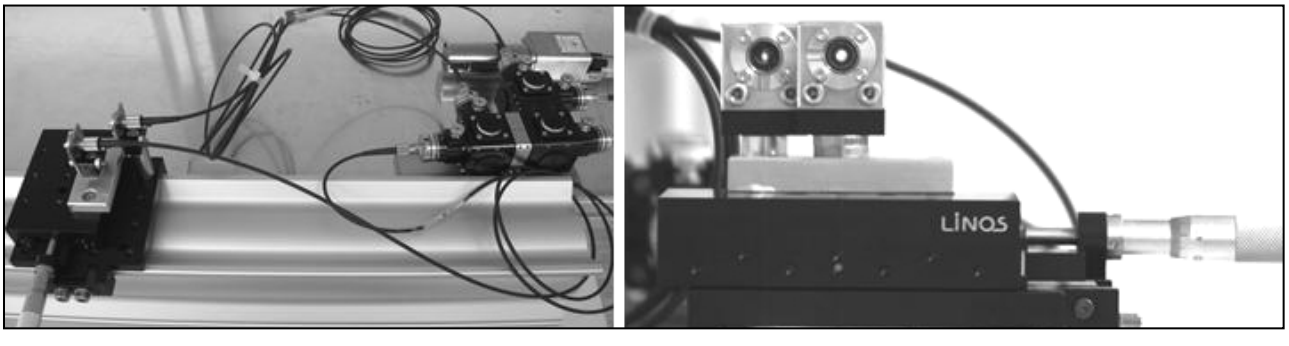

Figure 10 (a): Laser with beam splitter and fiber optics; (b): Configuration of the fiber Optics in front of the camera

In the first setup with a length of 1.2m the mean error between the actual distance translated and the calculated distance was 3µm. For the second setup with a length of 1.7m the mean error was 10µm. All tests have been measured in four epochs with translation of the fiber optics from 0.20mm up to 2.00mm perpendicular to the beam.

5 PERSPECTIVE

The first main task in the future development is to work out advantages and the disadvantages of the Poisson alignment system and the Active-Light-Source alignment system. That includes image processing with the tests of various algorithms especially cross correlation, precise measurement of the translation using an interferometer and simulations for expanding and focusing of the laserbeam using ZEMAX software. The cross correlation algorithm will deliver an accuracy of less than a tenth of the pixel size (Prenting, [4]).

The second main task is to test both alignment systems with a longer setup length. That includes building a vacuum system for the optics over 55m in length. For the Active-Light-Source system it is necessary to test the possibility of getting a sharp image of every target over the complete system length which means that all targets have to be on the field of depth of the detector optics.

References

[1] ***Griffith, L:*** "The Poisson Line as a Straight Line Reference", Lawrence Livermore National Laboratory Livermore, California, USA, 1989.

[2] ***Feier, I., Friedsam, H., Penicka, H:*** "The Poisson Alignment Reference System Implemebtation at the Advanced Photon Source", Argonne National Laboratory, Argonne, Illinois, USA, 1997.

[3] ***Meschede, D.:*** "Optik, Licht und Laser", page 74-78, B. G. Teubner Verlag / GWV Fachverlag GmbH, Wiesbaden, Germany, 2005.

[4] ***Prenting, J.J.:*** „Entwicklung eines Meßsystems zur automatischen Erfassung differentieller Punktverschiebungen im Objektraum", Dissertation, DGK Reihe C, Nr. 514, München 2000