High Precision Alignment at the European Synchrotron Radiation Facility

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SUMMARY

The European Synchrotron Radiation Facility (ESRF) is an accelerator laboratory located in Grenoble – France. It is supported and shared by 20 countries. The ESRF operates the most powerful synchrotron radiation light source in Europe.

The ESRF is a circular particle accelerator close to 1 km in circumference that produces many beams of bright X-ray light. Each beam is guided through a set of lenses and instruments called a beamline, where the X-rays illuminate and interact with samples of material being studied. Many countries operate synchrotrons—there are 10 in Europe—but only four worldwide are similar in design and power to the ESRF. Synchrotrons provide flexible, powerful methods for learning about the structure and behaviour of matter at the molecular and atomic level. Scientists use the ESRF to explore everything from exotic states of matter to snake fossils to the reason why chocolate sometimes develops a white film when it melts. There are dozens of highly specialised techniques for using synchrotron X-rays, each with its own strengths and applications.

The ESRF beamlines and their experiments cannot function without high precision alignment. Typically tolerances are less than 1 mm and often in the order of a few tens of microns over distances ranging between 70 m and 200 m. We will discuss some of the techniques that are used to achieve these extremely tight tolerances.

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1. INTRODUCTION

A particle accelerator is a machine that uses electric fields to accelerate ions or charged subatomic particles such as electrons and protons to high speeds while maintaining them in well-defined trajectories. Beams of high-energy particles are useful for both fundamental and applied research in the sciences. Fundamental particle physics seeks to understand the elementary constituents of matter and radiation and the interactions between them. Elementary particle physicists use machines that accelerate beams of particles such as electrons, positrons, protons, and anti-protons to the highest possible energies, generally hundreds of GeV[1] or more. Nuclear physicists and cosmologists use beams of atomic nuclei[2] of atoms such as iron or gold, to investigate the structure, interactions, and properties of the nuclei and of condensed matter at extremely high temperatures and densities similar to those imagined to have occurred in the first moments of the Big Bang. Interactions or collisions can be provoked between the particle beam and a fixed target or between two particle beams circulating in opposite directions within the accelerator[3].

Another branch of particle accelerator science uses what is referred to as synchrotron radiation. Synchrotron radiation light sources can be compared to *super microscopes*.[4] When high energy electrons are forced to change direction they emit extremely bright and coherent beams of ultraviolet and/or X-ray light. The electrons can be forced to change direction by passing through a bending magnet (dipole) or through specially designed periodic magnetic structures composed of many magnets with a special repeating row of N and S poles that force the electrons into a sinusoidal or helical path[5]. Application fields for light generated by synchrotron radiation light sources include chemistry, earth science, condensed matter physics, biology, and life sciences and technology. Examples of these types of accelerators are the ESRF, APS, SPRING-8, DIAMOND, the Canadian and Australian Light Sources (CLS and ALS), to name only a few.

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[1] The electron volt (eV; 1 GeV is 10^9 eV) is a unit of energy used in physics. By definition, it is equal to the amount of kinetic energy gained by a single unbound electron when it accelerates through an electric potential difference of one volt. By mass-energy equivalence, the electron volt is also a unit of mass. It is common in particle physics, where mass and energy are often interchanged, to use eV/c^2 , where c (a constant) is the speed of light in a vacuum (from $E = mc^2$).

[2] Nuclei are atoms stripped of their electrons leaving only protons and neutrons.

[3] Examples of these types of accelerators are CERN, DESY (until 2007), SLAC (until 2008), KEK and FERMI (until 2011) lab.

[4] With our eyes we can observe the macroscopic world. However, to *see* atoms, which have dimensions of the order of a tenth of a nanometre (i.e. 10^{-9} m), we need to use a different form of *light*, one that has a much shorter wavelength than visible light. This type of *light* is known as X-rays. Synchrotron light sources produce very intense and *bright* X-rays. X-rays have many well-known applications in medicine, but they can also be used to reveal important information about the organisation of the atoms that make up a material.

[5] These devices are called wigglers or undulators.

Virtually all accelerators, regardless what they are used for require precise alignment to function correctly. The field of accelerator alignment overlaps the fields of metrology and traditional surveying and geodesy. Standard measurement precision is millimetric to sub-millimetric over distances ranging between several hundred metres up to nearly 30 km. New and planned machines go beyond even this, requiring micro-metre alignment precision on the same scales. The use of specialised techniques and instruments are needed to guarantee that these requirements can be met.

2. HIGH PRECISION ALIGNMENT AT THE ESRF – A CASE STUDY

2.1 Introduction

The ESRF - the European Synchrotron Radiation Facility - is the most intense source of synchrotron-generated light, producing X-rays 100 billion times brighter than the X-rays used in hospitals. These X-rays, endowed with exceptional properties, are produced at the ESRF by the high energy electrons that race around the storage ring, a circular tunnel measuring 844 metres in circumference. Each year, the demand to use these X-ray beams increases and thousands of scientists from around the world come to Grenoble, to access the 43 highly specialised experimental stations, called “beamlines", each equipped with state-of-the-art instrumentation, operating 24 hours a day, seven days a week.

Thanks to the brilliance and quality of its X-rays, the ESRF functions like a "super-microscope" which "films" the position and motion of atoms in condensed and living matter, and reveals the structure of matter in all its beauty and complexity. It provides unrivalled opportunities for scientists in the exploration of materials and living matter in a very wide variety of fields: chemistry, material physics, archaeology and cultural heritage, structural biology and medical applications, environmental sciences, information science and nanotechnologies.

Precision alignment is essential for the beamlines to work and perform the high quality science. The field of accelerator alignment is vast and there are many different and varying application examples. The simplest way to appreciate the accelerator alignment issues is to work through a real example. At synchrotron radiation facilities grazing mirrors are used to steer the beams of X-rays used to image and interact with matter. The specific case study discussed here is the alignment of a mirror on the ID16 beamline.

2.2 X-rays and Science Background

The entire world of synchrotron science depends on one physical phenomenon: When a moving electron changes direction, it emits energy. When the electron is moving fast enough, the emitted energy is at X-ray wavelength.

A synchrotron machine exists to accelerate electrons to extremely high energy and then make them change direction periodically. The resulting X-rays are emitted as dozens of thin beams, each directed toward a beamline next to the accelerator.

Why use X-rays? X-rays are electromagnetic waves like visible light but situated at the high energy/short wavelength end of the electromagnetic spectrum, between ultraviolet light and gamma rays. Typically wavelengths range from 0.01 to 10 nanometres. The wavelength of X-rays used at the ESRF are in the order of 0.1 nanometre. This wavelength is comparable to interatomic distances, which makes X-rays suitable for the study of atoms and bonds.

There are dozens of highly specialised techniques for using synchrotron X-rays, each with its own strengths and applications. In very general terms, though, the light produced at the ESRF has qualities that make it good for the following kinds of problems, whether for basic research or for industry:

- Measuring hard-to-detect quantities or properties, e.g. when a structure is very small, a sample is tiny or very dilute, or an effect is faint.
- Observing physically hidden features, e.g. the buried portion of a fossil or the structure of a surface under a coating.
- Stimulating atomic and molecular processes that require a lot of energy, e.g. identifying the chemical state of heavy elements such as chromium or uranium.
- Observing processes that happen very fast, e.g. structural changes in biological proteins.

So science at the ESRF covers many fields. One particularly interesting and important field is medicine. And one very important medical application is understanding and curing disease.

With approximately 250 million cases and 781,000 deaths reported in 2009, malaria remains the most important human parasitic disease. Among the five Plasmodium species that infect humans, P. falciparum is responsible for most cases of severe disease and death, mainly in children under five years of age in Africa. An acute need for new drugs exists as resistance has developed to all antimalarial drugs. Thus, overcoming the problem of drug resistance is an essential goal of antimalarial drug discovery. The new synthetic compound ferroquine (SSR97193) provides new hope in the fight against malaria. An interdisciplinary team of researchers from Université Lille 1, Institut Pasteur de Lille, Grenoble Institute of Neurosciences and the ESRF have used a synchrotron-based nano-imaging technique to localise unlabelled antimalarial drugs inside single red blood cells infected by P. falciparum. The nanoprobe end station of beamline ID22 allows the simultaneous acquisition of the fluorescence signature of most elements of biological interest. Thanks to its exceptionally fine and bright focussed X-ray beam, the end-station permits the imaging of trace elements with a spatial resolution of 50 nm at detection limits down to the attogram level. [1]

Imaging nanometre sized objects such as the parasite P. falciparum requires a very long beamline. The new ESRF ID16 beamline is dedicated to nano-imaging and nano-analysis. The experimental station is 185 m from the source X-rays located in the accelerator. The challenge is to shine the X-ray beam which is less than 1 mm in diameter onto the experimental specimen. To make matters more complicated the X-ray beam is reflected by a mirror.

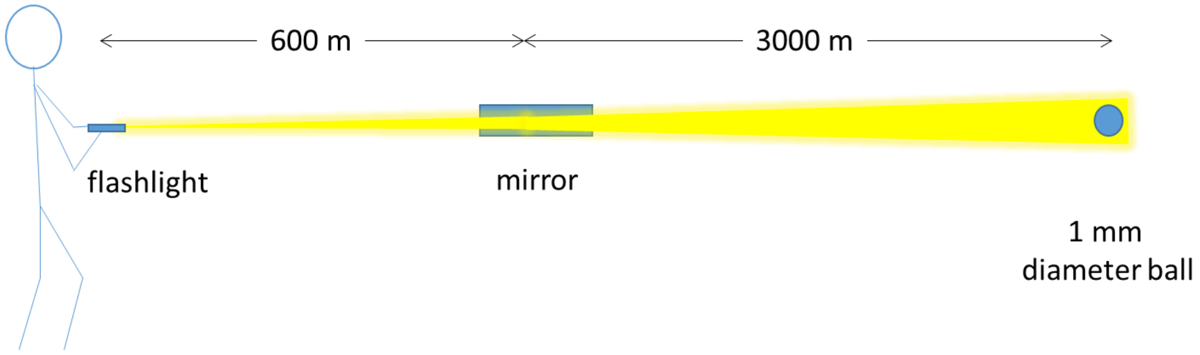

Figure 1 To appreciate this alignment challenge, consider shining a 20 mm diameter flashlight beam onto a mirror located 600 m away from where you are with the flashlight, and aiming so that the reflected beam illuminates a 1 mm diameter ball located at a distance just over 3 km from the mirror.

2.3 Survey Networks

The ESRF survey networks form the skeleton upon which all of the high precision alignment is pinned. There are actually several interlocking survey networks (see Figure 2). Taken together they comprise over a thousand points.

All of the ESRF networks, except for the exterior network which is not discussed here, are measured using AT401/2 laser trackers. The coordinate uncertainties issued from the least squares calculation vary across the site but are always less than 1 mm in *X*, *Y* and *Z*. More importantly, locally relative uncertainties between the accelerator (machine) and the beamline are much smaller – in the order of 0.2 to 0.5 mm[6]. These uncertainties degrade with time, so to maintain precision, the main networks are measured frequently – at least twice per year.

Generally experimental instrumentation is located in lead lined hutches. However, each beamline is unique. Survey networks are also installed in the experimental hutches. These hutch networks are connected to the main ESRF networks. Figure 4 shows a typical beamline network and the observations to the main EXPH network required to define the network in a series of experimental hutches.

[6] Relative *X*, *Y* and *Z* uncertainties at the ID16 beamline end station located 185 m from the machine are in the order of 1 mm.

Figure 2 Overview of the different main ESRF survey networks.

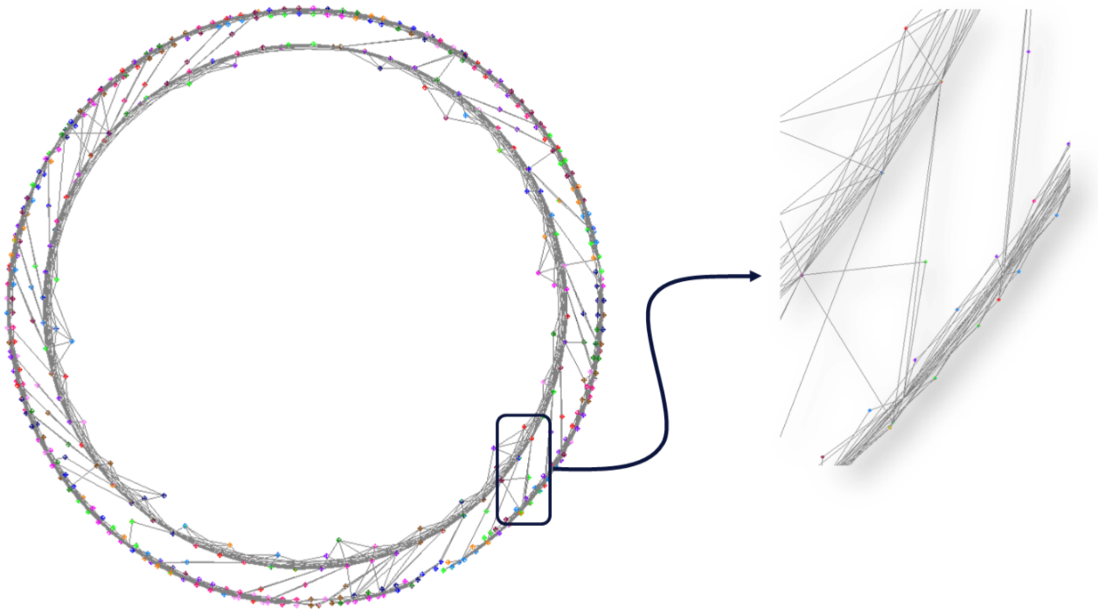

Figure 3 This image shows the EX2 survey network. It is one of the ESRF networks comprising several hundred points measured by highly redundant 3D observations - horizontal and vertical angles, and slope distances. It forms the backbone for the individual beamline networks. Grey lines show laser tracker observations.

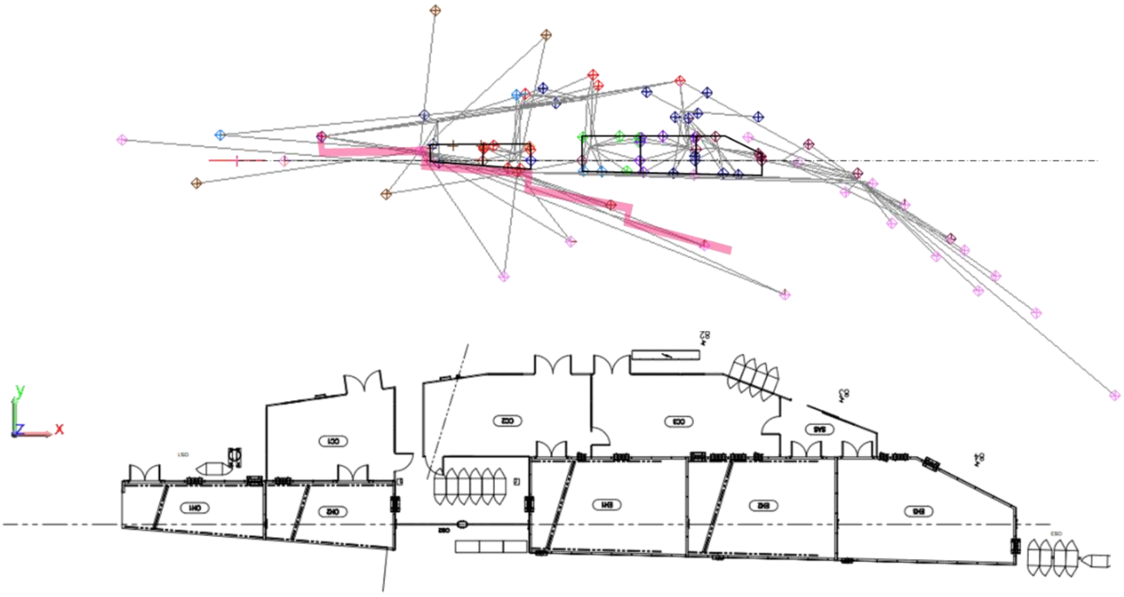

Figure 4Typical beamline reference point network. The top part of the figure shows the network with the outline of the beamline hutch walls. The experimental hutch layout on the same beamline is shown in detail in the lower part of the figure. The photon beamline axis is shown as a dashed line in the top and bottom parts of the figure. Grey lines represent laser tracker observations made from the main ESRF network to the experimental hutch networks.

2.4 Mirror Alignment

The X-rays that are used to study matter and life systems are generated by electrons accelerated and stored in the Storage Ring particle accelerator. They are emitted tangentially along the travel of the electron beam. For a variety of reasons scientists want to interact with the X-ray beam and change its direction. For physical reasons, X-rays can only be steered or reflected using grazing angle mirrors. Reflection angles are typically less than 10 mrad (i.e. less than 0.5 degrees).

We are used to seeing reflections in a mirror that is oriented at much larger angles. For example, generally we look at ourselves face-on in a mirror (i.e. 90°). Or we can look at what is outside through the reflection we see in a door that is ajar 45° to where we might be sitting or standing. However, it is difficult to appreciate what a mirror oriented at 8 mrad physically looks like.

Consider a 500 mm long mirror. When it is turned 45 degrees the part of the mirror we see is 353 mm wide (i.e. $353 \text{ mm} = 500 \text{ mm} \times \sin(45°)$). When it is turned 8 mrad to us, it presents a face that is just 4 mm wide (Figure 5). In fact our eye would not be able to distinguish the reflection. However, it works very well for X-rays. But it means that the mirror must be very precisely aligned both in orientation angle and in position so that the photon beam actually is incident upon it.

First consider the position. The photon beam is coming from the machine which is approximately 30 m away. The mirror must be aligned so the centre of the photo beam is incident of the centre of the mirror. If the photon beam is to be within say ±5 mm of the centre of the mirror then the mirror must be aligned to within$\pm 5\text{mm} \times 0.008 \text{ rad} = 0.04 \text{ mm}$. Now consider the orientation of the mirror. It must reflect light that will hit a 1 mm diameter object located at 155 m from the mirror. So the mirror orientation must be within $0.001 \text{ m}/155 \text{ m} \cong 6$ μrad or 1.5 arc-sec. These tolerances are quite challenging.

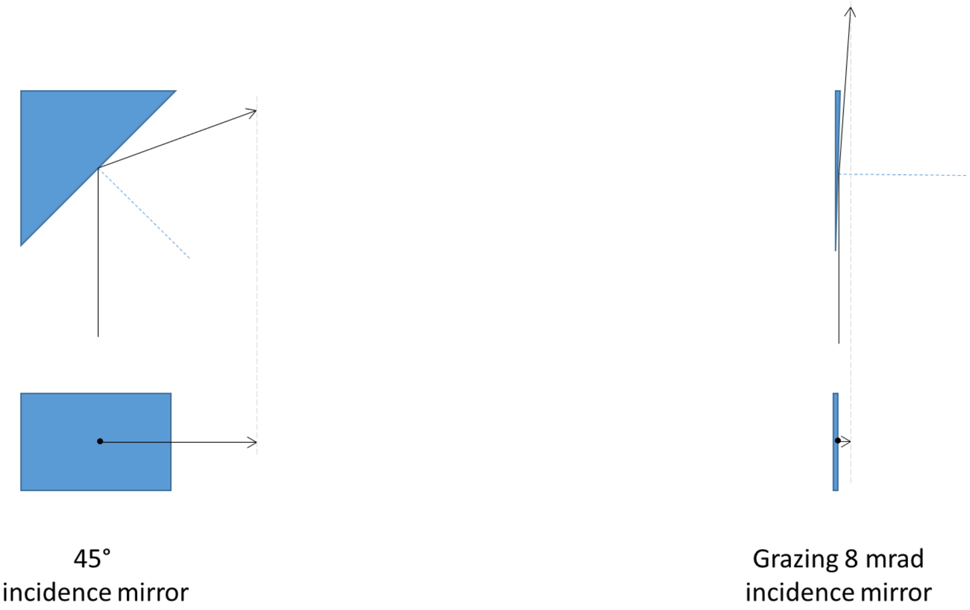

Figure 5 On the left hand side a mirror rotated 45° to an incoming beam lof light. On the right a mirror rotated at a grazing angle of 8 mrad to an incoming beam of light.

To make things slightly more complicated, the mirror is installed in a vacuum chamber and is not visible when the chamber is closed (see Figure 6)

So how is this alignment accomplished? It is actually made in several steps. First the mirror is measured and characterised in a clean room with respect to external reference marks that can be seen when the mirror is enclosed under vacuum and no longer accessible or even visible. These measurements are made with AT401/2 and AT901 laser trackers. As can be seen in Figure 6 certain surfaces are also measured using the AT901 Tprobe. The orientation of the mirror with respect to the external reference marks is measured using the high precision auto collimation function of the AT401/2 laser tracker. This process is called fiducialisation.

When the mirror assembly is transferred and installed in-situ on the beamline the exterior reference marks and the beamline survey network are used to position and align the mirror.

3. SUMMARY

We have discussed how a mirror is aligned on one of the ESRF beamlines. This provides one example of how high precision alignment with tolerance less than 0.1 mm and a few arc-seconds can be accomplished.

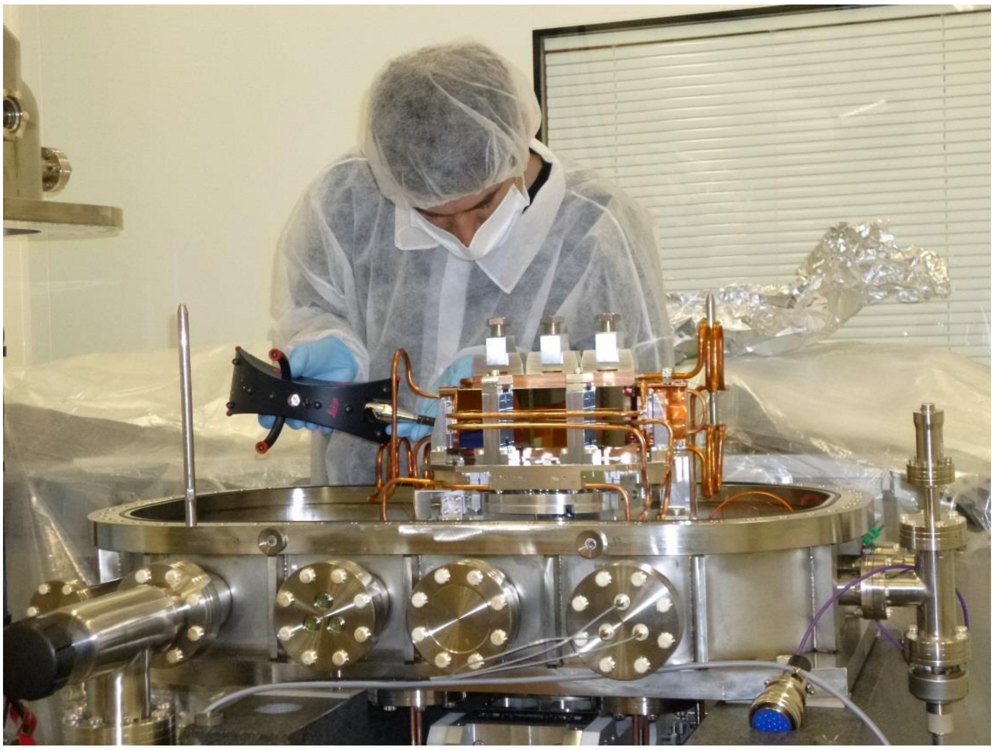

 

Figure 6 The mirror is installed in a vacuum chamber. It is not visible from the exterior when closed. Top and bottom left photos- the mirror being measured in a clean room. Bottom right photo - the mirror installed in situ on the beamline.Refernce marks on the granite support combined with the beamline survey network are used to align the mirror in –situ.

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BIOGRAPHICAL NOTES

David Martin is head of the ESRF Alignment and Geodesy Group. He holds an MSc in Land Surveying from the Department of Geomatic Engineering, University College London and a PhD in Engineering from the University of Warwick in the United Kingdom. He is the chair of FIG Standards Network and FIG Working Group 5.1 Standards, Quality Assurance and Calibration. He has published a number of papers concerning accelerator alignment, survey instrument calibration and hydrostatic levelling systems.

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