PRINCIPLES & STATUS OF SOLEIL ALIGNMENT SYSTEM

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1. INTRODUCTION:

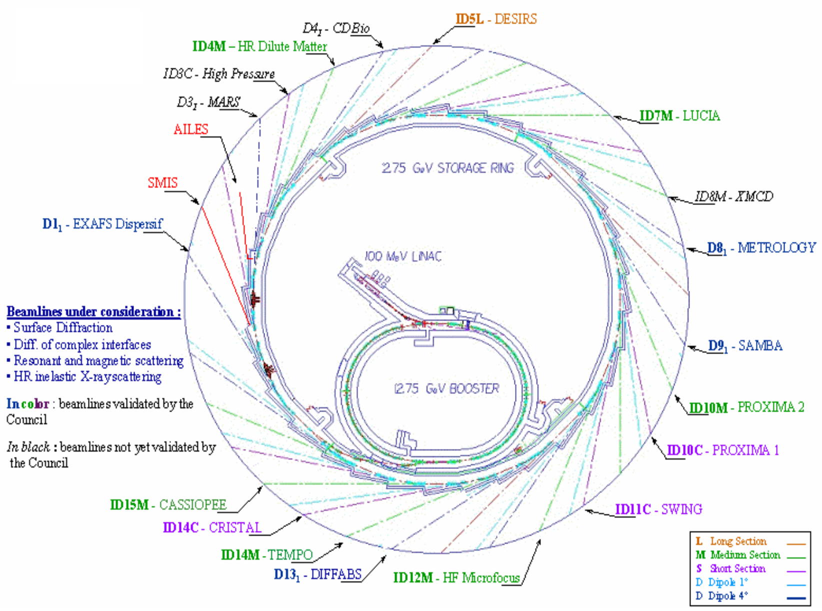
In the synchrotron facilities, the perfect alignment of the magnetic components is crucial to obtain a high quality beam in the point of view of its physical parameters as emittance and lifetime. But some other aspects are directly concerned by a high level quality of alignment in terms of both accuracy and methodology: the ability to inject the first beam (commissioning phase) without any a priori knowledge of the closed orbit, and the ability to easily correct the initial orbit in a reduced delay during maintenance phase.

2. SYNCHROTRON SOLEIL OVERVIEW:

2.1. A 2.75 GeV nominal energy:

The general characteristics of this third-generation synchrotron radiation source rank SOLEIL at the highest level of international competition. In the 1999 APD (Detailed Preliminary Project, or Avant-Projet Détaillé) **(1) (2)**, the energy of the beam in the storage ring had been fixed at 2.5 GeV, thus covering a broad spectral range from ultraviolet (5 eV) to soft X-rays (15 KeV). Since then, taking into account the increasing demand for the use of hard X-rays, namely in the crystallography of biological macromolecules, the SOLEIL team has optimised the accelerator to 2.75 GeV in order to enhance the performance of the machine in the field of X-rays.

Figure 1: general overview



2.2. The accelerator:

The electron beam is created in the 13m long linear accelerator and then, feeds the booster after having passed through a first transfer line (LT1). The booster accelerator split up in 36 girders supporting dipoles, quadrupoles and sextupoles. Five straight sections located along the 156.620m of its circumference will receive injection & extraction components, and also the RF cavity.

The physical study of the accelerator part led to an optical design composed of four super-periods, each divided in four cells. The multipole magnets (quadrupoles & sextupoles) are distributed on 56 steel girders. 32 dipoles bend the electron beam all along 354,097m of the storage ring circumference.

2.3. The beam lines:

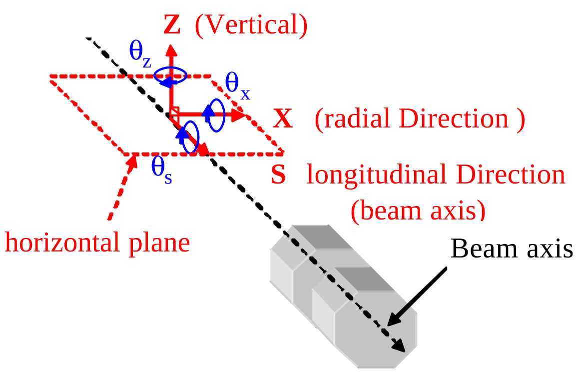
The project for the machine developed during the 1999 APD phase provided for the installation of at least 14 beam lines on these undulators, and 26 other light exits on bending magnets, for a total of 43 possible lines.

SOLEIL will start operating in spring 2006 with 10 beam lines, 5 of which will be transferred from LURE, to reach 24 operating beam lines by the end of 2009.

3. POSITIONING SPECIFICATIONS:

The theoretical studies of the accelerator part allow defining for each family of component the values of the necessary accuracy in terms of positioning. The following figures are given in standard deviation (σ) for the 6 DOF[1] of each component, considered as a solid in the 3D space. We will keep in the future that 3D approach by creating a DOF management database for the whole project, including machine and beam lines component.

Figure 2: Definition of the referential triedre



The positioning standard deviations of the 6 DOF are given in the following machine referential given in the fig. 2.

3.1. Storage ring positioning specifications (2):

The most critical values are the ones underlined in the table below, i.e. the X, Z, θ_S of quadrupoles & sextupoles and the θ_S of the dipoles: The other parts of the machine present similar values, slightly relaxed.

Figure 3: Storage ring positioning specification

	Dipoles	Qpoles & Spoles	Girder/girder
σ_S (mm)	0.50	0.20	0.50
σ_X (mm)	0.50	<u>0.02</u>	<u>0.05</u>
σ_Z (mm)	0.50	<u>0.02</u>	<u>0.05</u>
$\sigma_{\theta S}$ (mrad)	<u>0.10</u>	<u>0.10</u>	<u>0.10</u>
$\sigma_{\theta X}$ (mrad)	0.20	1.00	1.00
$\sigma_{\theta Z}$ (mrad)	0.20	1.00	1.00

3.2. Alignment strategy:

Several basic precautions must be kept in mind in order to reach theses accuracies for the positioning of such accelerator.

[1] DOF : Degree Of Freedom

The first basic principle to be applied is to keep as close as possible to the functional element i.e. the magnetic definition of the magnets for example. A special effort must be made to reduce intermediate steps or indirect measurements during the positioning operations. Applying this fundamental principle, a “relative” approach is preferred to an “absolute” one, i.e. the shape of the machine (rings, linac, transfer lines) will be considered first. In this approach, the geodetic networks (site & tunnel reference networks) are not used as conventional “fixed points”. In the long term, an approach of mixing optical & Beam Based Alignment should fulfil that principle.

The second basic principle to be applied is to prefer measuring the real location of the mechanical references (survey monuments) instead of adjusting them at a theoretical one. It induces an overload data management that could nevertheless, lead to an improvement of accuracy by taking account of the offset. Any reference materialization, whatever its use (survey monument, machined surface), has to be accurately located related to the functional element of its referred component (magnetic axis of a magnet).

In parallel, as mentioned previously, a 3D approach will be carried out in considering the 6 DOF of any machine or beam line component. Consequently, DOF management database will be created.

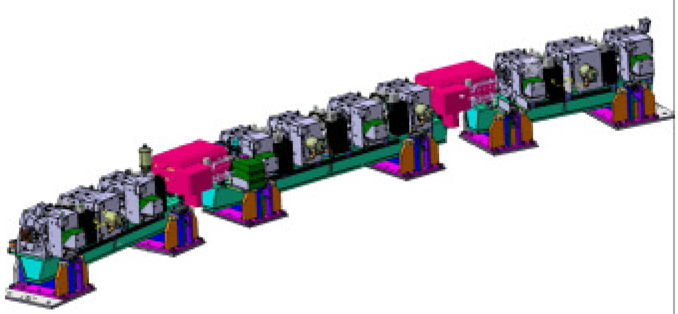
Finally, we intend to target the ultimate accuracy in terms of alignment in order to anticipate new needs of users about the quality of the beam. It means that, in the first instance, a special effort has to be made on magnet alignment related to the girder.

A high level quality implies taking into account the practical aspects especially of the tunnel operations. Since the alignment operation is very sensitive to the surroundings (stability, visibility), the design of mechanical systems for positioning & survey is of major importance to achieve a reduced delay for the whole operation.

4. THE STORAGE RING REVIEW:

Since the storage ring represents the heart of the accelerator, we will now review in details its design in terms of positioning. The "Conception & Ingenierie" Group of Soleil has managed the mechanical design according to the "Alignement/Métrologie" Group requests for the positioning design.

Figure 4: Storage Ring cell (2-dipole configuration)



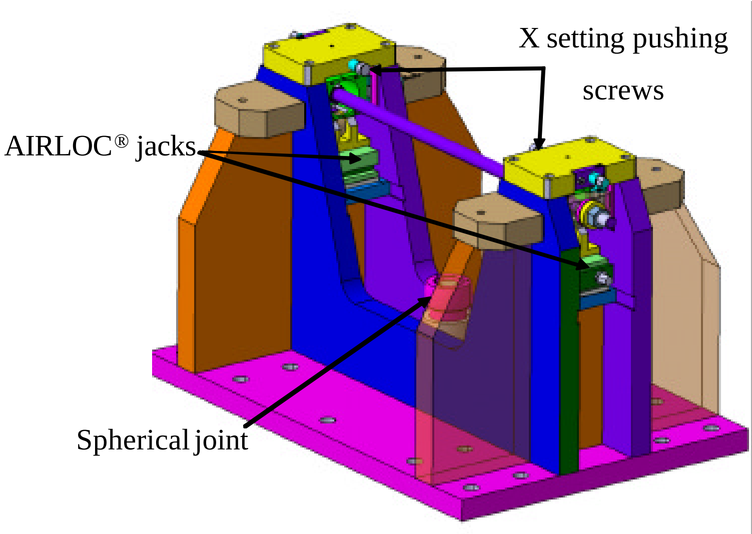
4.1. The girder & stands design:

The SR cells are composed either of two adjacent girders supporting a dipole, or of three girders supporting two dipoles (see fig. 4). The lack of space around the dipoles led to that designs for their supporting system.

The main idea is to separate the adjusting and holding functions of the girders: 3 jacks and 4 binding points are necessary. The benefits are as following: isostatism makes settings and alignment easier, the jacks can be simple, no need for great horizontal stiffness. In addition, the clamping on the 4 binding points increases stiffness and then, the dynamic behaviour. A spherical joint under the girder defines its longitudinal location. The 2-

Jacks girder stands configuration is presented in fig. 5. The other stands have only one jack, located underneath the girder.

Figure 5: SR Girder stands (2 jacks)



4.2. The girder measurements:

4.2.1. Flatness measurements:

There are four types of girders in the storage ring, whose lengths are contained between 3,5m and 5,0m. The design gives very strong and stiff structure with a good dynamic behaviour. Since the girder itself is used as an alignment reference for the magnets, the machining phase demands great care. 0.02mm flatness envelope was successfully achieved on the four first girders that have been checked. The fig. 6 shows the results of checking measurements on a long girder. These measurements have been realised with a Micro-Contrôle STR500 alignment laser and a Leica NIVEL20 clinometer (fig. 7). The *a posteriori* accuracy of the measurement method is estimated better than 5µm.

After having loaded the long girder with false magnets that simulate the real distribution of the weight, a deflexion measure has been realised: it is approximately around 10µm, value in good accordance with the theoretical calculation.

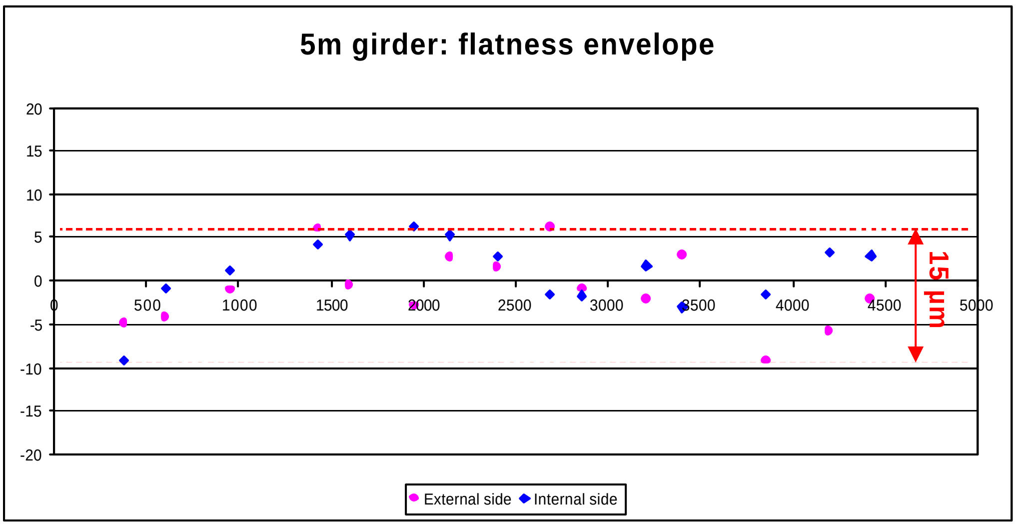


Figure 6: "As made" flatness measurements of long girder

(the deflexion due to the magnets load is 10mm approx.)

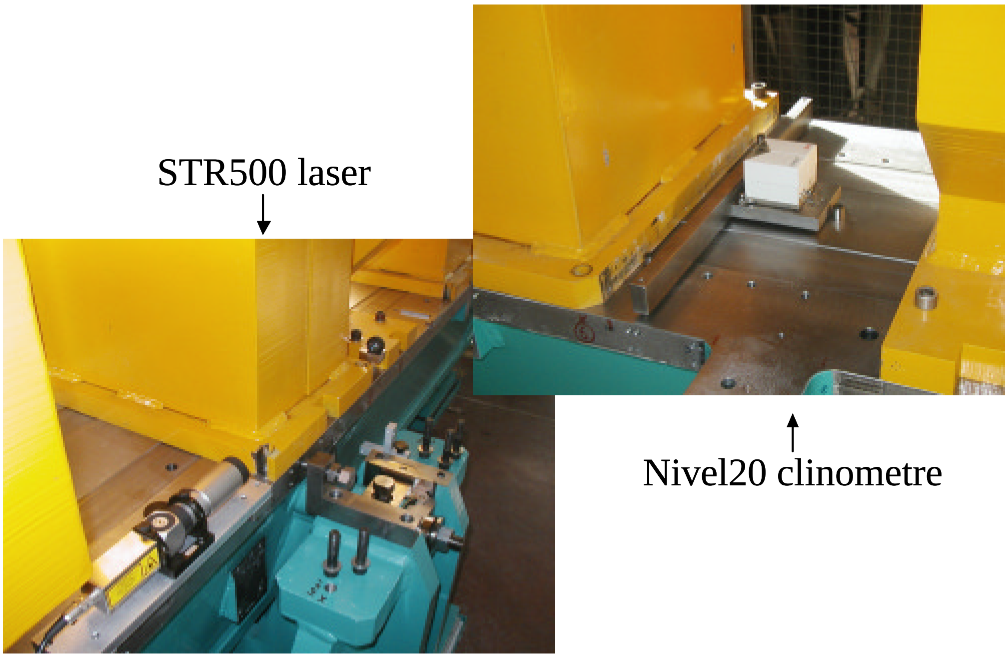
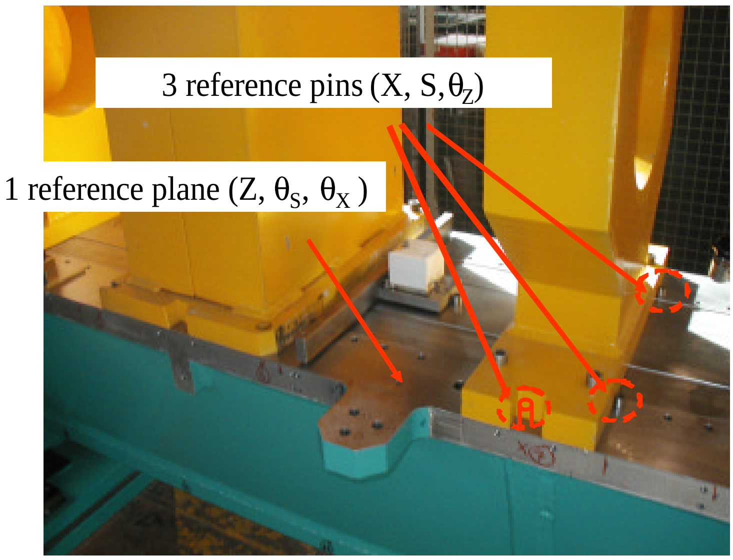


Figure 7: Instrumentation for flatness measurements

(the girder is equipped with false magnets for static & dynamic tests)

4.2.2. Alignment pins & shimming operation:

Figure 8: Mechanical references of the girder



Each magnet is horizontally aligned by the mean of a pin mounted on the upper face of the girder on which it leans laterally (see fig. 8). The ability to align the magnets depends on the quality of the alignment of the pins. A campaign of measurement is still in progress. Nevertheless, a machined steel shim mounted between each magnet and its lateral pin allows correcting the magnetic defaults in the horizontal direction (X) for the Qpoles & Spoles. Similar shims also exist for the vertical direction (Z) and tilt (θ_S) underneath the magnets. This operation stands on the BMS, magnetic measurement bench (see fig. 9).

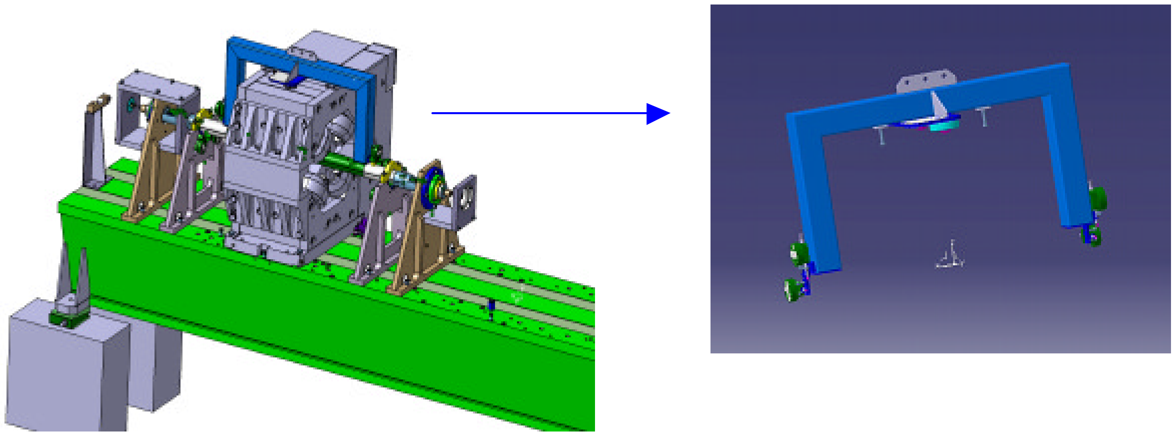


Figure 9: BMS (Banc de Mesure Soleil), a bench for magnetic measurements & the " magnet comparator "

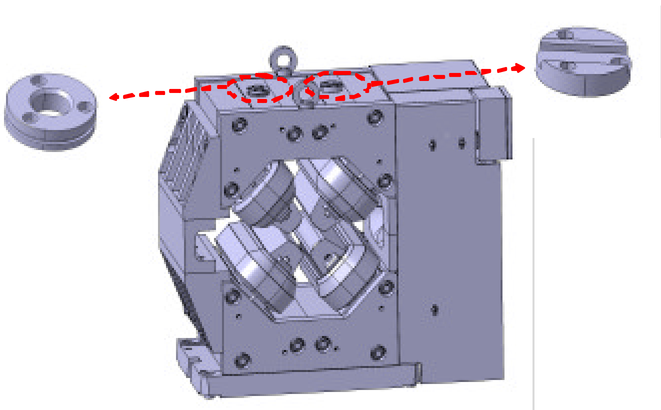
4.3. Surveying & positioning the magnets on the orbit:

4.3.1. The BMS (Banc de Mesure Soleil):

The beginning of the alignment procedure starts on the magnetic measurement bench BMS where the horizontal & vertical shims are determined in order to correct mechanically the magnetic defaults of the Qpoles & Spoles.

At that step, we also measure the location of the survey monuments directly from the magnetic coil sensor that defines the magnetic centre of the magnet. That offset measurement is realised by the mean of a special support that receive four displacement sensors (electronic comparators). That tool can be considered as huge "magnet comparator", the measurements on a Qpoles being relative to each other.

Figure 10: Quadrupole survey monuments



4.3.2. Fiducialization of the magnets:

The Fiducialization must allow keeping the general accuracy of the mechanical machining. Therefore, we propose a new design for Soleil survey monuments that is slightly inspired by the CERN standard and the ESRF version. The used sphere diameter is 1,5” (ϕ38,10mm) instead of 3,5” (ϕ88,90mm); the monument is monolithic, without any possible adjustment to avoid any parasitic displacement. A special effort has been made to the quadrupoles which are fiducialized with a special pair of monuments: a cone and a Ve, that allows an isostatic centring system, common to ecartometre, clinometre and STR500 retroreflector prism. A short ϕ24mm bore hole (5mm length) coaxial to the cone is used for centring the theodolite. Most of monuments are shifted laterally, 100mm in the storage ring. Consequently, one can keep safe the sight lines on the straight sections of the storage ring.

4.3.3. The survey method:

The proposed method to align the storage ring consists in considering only the quadrupoles magnets as they are of a first importance in the definition of the beam orbit. Since they are more than two for most of the girders, they could lead to an improvement of the final accuracy in increasing redundancy in the location of the girders.

We intend to survey the storage ring with a wire ecartometre and a total station theodolite for the planimetry. A HLS[2] network used in an absolute way should define the altimetry of the 56 girders of the storage ring.

4.3.4. Instrumentation:

The chosen total station is the well-known Leica TDA5005 that we use with ø1,5" retroreflector. The ecartometre has been design especially for Soleil by the company "Symétrie" based at Nîmes, France. It could achieve 5µm accuracy with a 15m long Kevlar wire (delivery next month).

Figure 11: Instrumentation for the planimetric survey: SYMETRIE wire ecartometre & LEICA TDA5005

Figure 12: HLS sensor

The storage ring will be equipped of a HLS network (Fogale Nîmes, France) for the alignment of the 56 girders. Each girder has three HLS sensors linked by a 354m pipe all along the ring. The retained topology for the network is as following:

- All the pipes are common for air and water
- A collecting pipe runs along the ring from girder to girder, the HLS vessels are connected with smaller pipes
- Steel pipes, ø45 for the collecting pipe, ø22 for the connections

[2] HLS: Hydrostatic Levelling System

4.3.5. Method for the adjustment of the girders:

The main scheme is an iterative procedure comporting successively the following phases:

- Survey (planimetry & altimetry)
- Calculations (least square for planimetry, then conversion in terms of 6 DOF)
- Adjustment of the girders

The last phase separates mechanics and measure in terms of movements. It allows limiting the backlash and the negative effect of the clamping on the girder adjustment.

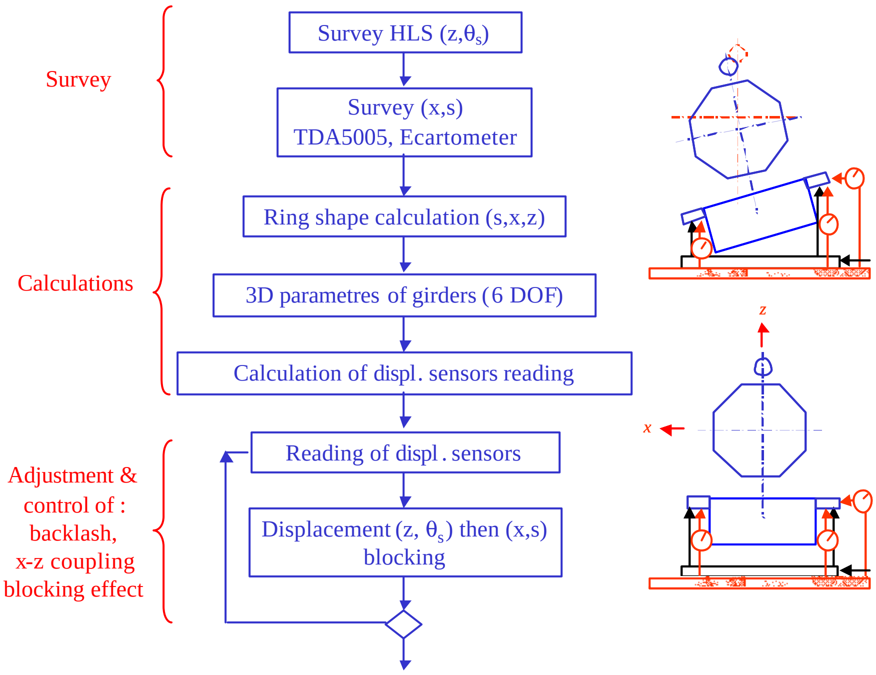


Figure 13: Adjustment procedure of the SR girders

4.4. Error budgets for the storage ring alignment:

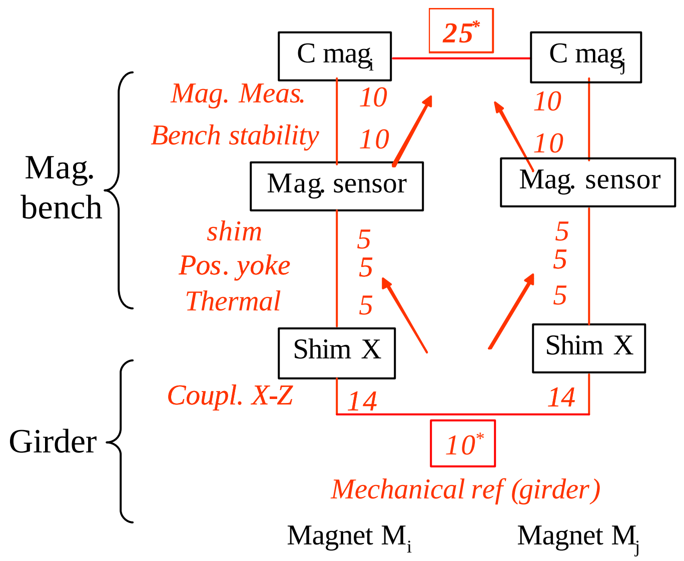
Studies have been realised in order to estimate the accuracies we could expect for the storage ring alignment. We insist on the fact that the following calculations must be used with a great care, considering the huge number of physical parameters that really influence the result of the alignment. The main interest of these results lies in the analysis of the links between the existing sources of errors. That is the reason why the graphical presentations of the error budgets show a dimensional aspect.

The following error budgets have been carried out in considering random errors only, i.e. without any bias. The shown values correspond to the standard deviation (1σ) corresponding to random variables and therefore the well-known law of random error combination is systematically used:

$s^2 = \sum_{i=1}^{n} s_i^2$ for n random errors.

4.4.1. Planimetric error budget for the magnet alignment on a girder:

Figure 14: Radial Hor. (1 s_x) Error budget: magnet/girder

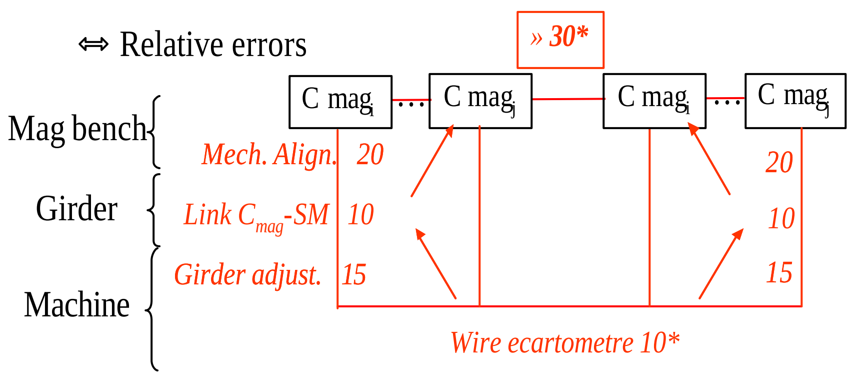


The planimetric error budget takes into account the measurements realised on the BMS and the machining quality of the girder. This includes the measurement chain from the magnetic centre of a quadrupole to any other one, that is to say: the repeatability of the magnetic measurement, the stability of the bench itself (the measurement campaign for the totality of the quadrupoles should last 6 months), the quality of the shim realisation, the repeatability of the upper yoke positioning (since it will be dismounted to install the vacuum chamber), the thermal uncertainty and finally, the quality of the mechanical references machining of the girder.

These errors lead to a resulting standard deviation (1σ) for the relative positioning of two magnets on the same girder approximately equal to 25µm (see fig. 14).

4.4.2. Planimetric error budget for the girder alignment:

Figure 15: Radial Hor. (1 s_x) Error budget: girder/girder



The following calculation allows estimating the expected alignment accuracy for magnets located on two adjacent girders. In other words it can be seen as the accuracy of a local smoothing adjustment. The possible sources of errors are: the mechanical alignment previously presented, the use of the magnet comparator, the girder adjustment system (due to clamping effect) and then, the wire ecartometre measurement. The combination of them gives an estimated accuracy (1σ) around 30µm (see fig. 15).

Nevertheless, it is advisable to consider this value just as an ultimate accuracy to target instead of sure information. It exists a universal law in metrology, whatever the size of the structure: the bigger the structure to be measured, the lower the corresponding accuracy.

4.4.3. Survey errors simulations:

Simulations were made with ©Matlab software in order to estimate the impact of measurement errors (wire ecartometer & TDA5005) on the global shape of the storage ring: it results that the theoretical uncertainty envelope of the orbit is better than 0,1mm (1σ). Nevertheless, this value seems slightly optimistic since the measurement stay sensible to the surroundings conditions. Besides that instrumental error, one must add the term corresponding to the survey monument link to the magnetic centre seen in the pervious paragraphs. The fig. 16 shows the expected resulting errors.

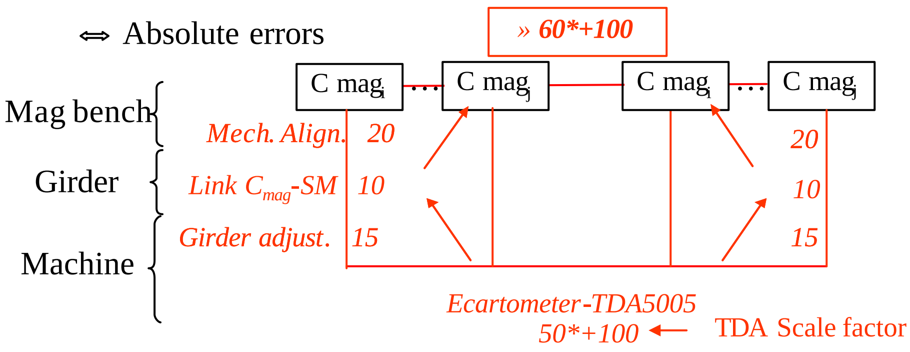
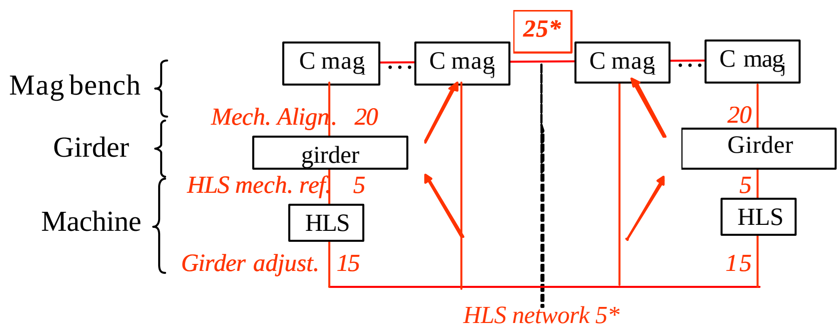


Figure 16: Simulation of the combination of magnetic-mechanical errors with TDA5005 errors

4.4.4. Altimetric error budget for the magnets alignment:

Figure 17: Radial Vert. (1 s Z) Error budget: magnet/girder



The altimetric error budget for magnets on the same girder is the same as for the planimetric one, except that the coupling term (X-Z) does'nt exists anymore. One can then achieve 20µm (1σ).

The alignment of the girders is realised by the mean of the HLS. The next figure shows the expected accuracy of such adjustment. The error path going from a magnetic centre to any other one on any other girder includes: the mechanical alignment previously presented, the girder adjustment system (due to clamping effect) and then, the HLS measurement. The combination of them gives an estimated accuracy (1σ) around 25µm (see fig. 17).

The term corresponding to the HLS measurements (σ=5µm) is subject to long term variation, due to slow drift [(4)]. Therefore, the resulting 25µm value can vary along the year to about 30µm.

5. THE ALIGMENT OF THE BEAM LINES:

5.1. The strategy of beam line alignment:

The beam line optical designers retain 2 principles:

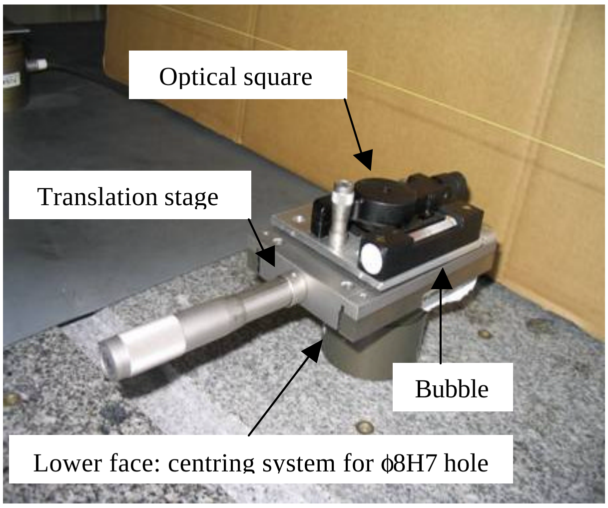
- The Alignment/Metrology group pre-positions the beam line components for their definitive alignment under beam by the Optics group. It's the most common way. It is supposed that the component can be equipped with actuators whatever their design, to move it according to the necessary DOF.

- The Alignment/Metrology group aligns directly and accurately the components in their definitive position or according to the necessary DOF. For example, the positioning of the first mirror being on many beam lines critical for the downstream beam alignment, it could be decided to strongly clamp their concerned DOF.

5.2. Choice of reference points:

Considering that the photon beam comes from the upstream dipole or straight section, the used reference points will be the ones of that straight section. Sight windows through the tunnel wall allow reducing intermediate steps in the alignment procedure. Consequently, one can rely on direct transfer for the measurements between the storage ring and the beam line components.

Figure 18: mini wire ecartometre

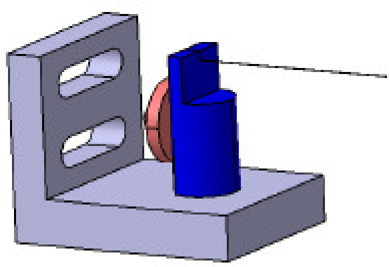


5.3. Instrumentation:

The usual instruments for beam line alignment are used at SOLEIL: theodolites (typically the accurate Leica TM5100A) and levelling machine. In addition to that, we have successfully tested a stretched wire alignment method at LUCIA (the first operating SOLEIL beam line set up at SLS), based on a small optical square mounted on manual translation stage. It is planned to extend that method at the whole beam lines at SOLEIL (see fig. 18).

5.4. Fiducialization:

Figure 19: Beam line reference point



The component of the beam lines will be fiducialized in a very light way, considering that the major part of them could be adjusted thanks to mini-ecartometre. In that case, a ϕ8H7 hole is enough. However, These references can receive an interface cone to use a ϕ1,5" sphere as a target if necessary.

The beam line will be equipped with mechanical references fixed on the two end walls of every hutch: A simple square with a ϕ8H7 hole machined vertically to receive either the interface cone or the stretched wire extremity (see fig. 19).

5.5. Error budgets for the beam line alignment:

Studies have been realised in order to estimate the accuracies we could expect for the beam line alignment. We present only the case of beam line using undulators, but the one of beam line working with dipoles can be easily applied. We insist again on the fact that the following calculations must be used with a great care. The aim of these calculations is to estimate the positioning accuracy of a component related to the photon beam it sees.

The photons are generated by the corresponding machine components, i.e. the undulator on the straight section. Consequently, their location depends first, on the one of the electron beam and secondly on the orientation of the undulator.

On the other hand, the adjustment of the beam line component leans on the machine references of the concerned straight section in order to limit the error accumulation. Therefore, the error path going from the photon beam to the component includes: the location of the electron beam [5] (σ_{beam}), the orientation of the undulator [6] (σ_{undul} due to both, magnetic errors & alignment procedure), the link between electron beam & survey monuments and the instrument accuracy. We present the case of the X' orientation by theodolite autocollimation (see fig. 20). Many others calculations have been carried for the beam line alignment.

Notice that in this paragraph, the DOF vocabulary has slightly changed: X' instead of θ_Z and Z' instead of θ_X.

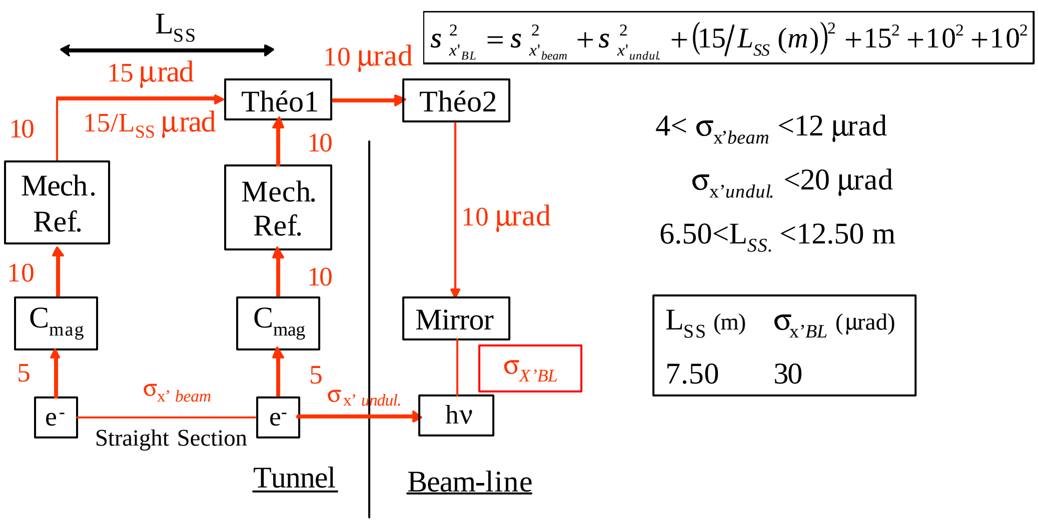


Figure 20: Error budget for X' orientation on beam line components

6. CONCLUSION:

The "Alignement/Métrologie" Group is now complete: five persons work on the main objective that is the machine installation starting in the coming days. We will soon apply the chosen strategy in details. However, The LUCIA beam line installed at SLS has been a first achievement for the whole SOLEIL team. The design phase is not completely closed and some improvements may occur during the coming months.

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