Alignment Strategy Used for the Positioning of the Magnets and Girders of the SOLEIL Storage Ring

Alain Lestrade, C. Bourgoin, E. Guigné, M. Jagu (ATGT), M. Ros, M. Sebdaoui
Synchrotron SOLEIL, GIF sur Yvette, France

The installation of the SOLEIL Storage Ring is being achieved, the commissioning with beam started in May 2006. A complete alignment procedure will have to be done, before, to achieve the tight positioning tolerances on the magnets and girders. We will describe the full procedure and the corresponding concepts of the Storage Ring Alignment, in terms of mechanics, magnetic measurements and geometrical measurements. The error budget of such a critical path of the alignment will be discussed and finally, the first results achieved at the commissioning start. The paper will also present original instrumentations, as the magnet comparator specially designed for SOLEIL and a tentative to use a dedicated HLS network as an absolute reference for the vertical alignment of the girders.

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 such as emittance and lifetime. The commissioning started in the beginning of May 2006 with a certain success in terms of alignment since the physicists obtained several turns of the storage ring without any beam correction and without the use of the RF cavity or the sextupoles at the occasion of the very first tests. In this paper, we will go through details of positioning the quadrupoles that define the storage ring orbit in terms of method and results.

2. THE ACCELERATOR

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

The most critical values in terms of positioning are the alignment of the Qpoles & Spoles on their own girder, expected within 0.02mm (1σ) in both horizontal (X) & vertical (Z) directions, and the position of the magnets related to the ones on the other girders, expected around 0.05mm (1σ).

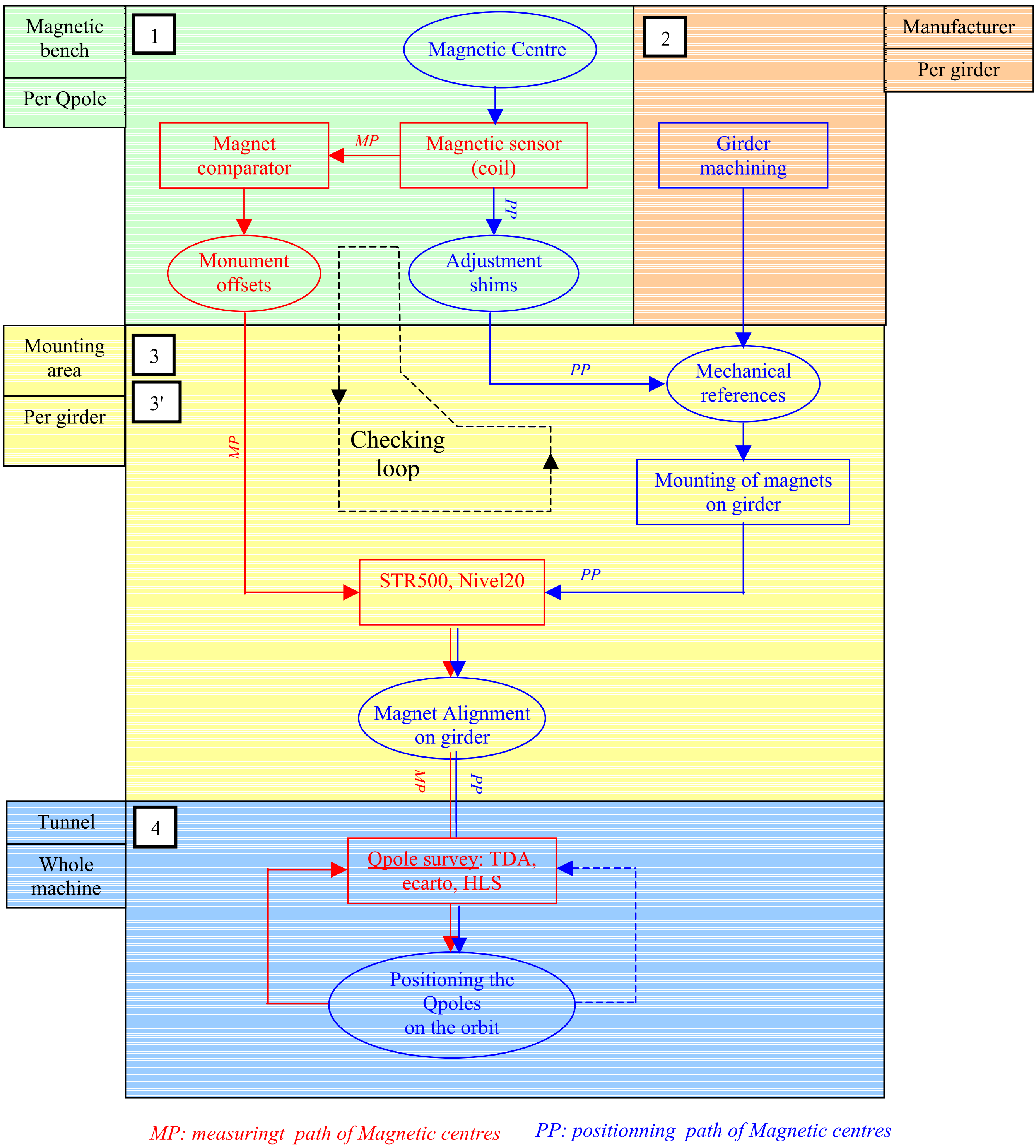


Fig.1: General scheme of the alignment procedure

3. GENERAL SCHEME OF ALIGNMENT

3.1. General scheme

We remind the general scheme for positioning the storage ring magnets, presented at IWAA2004 [1]. The numbers in brackets & italic refer to fig.1.

The Qpoles are mechanically aligned on their girder by means of machined mechanical references: the girder machined references on one hand and the Qpoles mechanical references on the other hand. The first step ***(1)*** consists in measuring on a magnetic bench (BMS) the necessary shim between the two surfaces in order to correct the mechanical/magnetic dispersion between all the Qpoles. Every Qpole magnetic centre (MC) is located related to the BMS mechanical references similar to the girders ones. At this occasion, the measurement of the survey monuments location is realized related to the magnetic sensor (coil) of the BMS with a "magnet comparator" ***(1)*** especially designed by SOLEIL. The 56 steel girders were manufactured at the same time ***(2)*** at the "établissements Roche", Reims, France. Then, every girder is equipped with its whole components including Qpoles in a mounting area ***(3)***. It is there that was planned the first step of checking measurements: the alignment of the Qpole magnetic centres is verified on each girder ***(3)***, leading to corrective actions if necessary on the Qpole position or the shim realisation. That third step is repeated inside the tunnel after having pre-aligned the girders ***(3')***. Finally, the standard method for aligning an accelerator is applied: survey and adjustments ***(4)*** are set in an iterative way until having reached the required precisions.

3.2. Measurements on the BMS magnetic bench *(1)*

The "Banc de Mesure Soleil" (BMS) is a magnetic bench designed for qualifying the characteristics of the multipole magnets and for the detection of their magnetic centre. These last measurements are obtained by means of a rotating coil. Since that coil represents the electron beam axis, we can measure and store the location of the magnet survey monument related to the coil when the Qpole is equipped with its right shim and in contact with the mechanical references of the bench. It is what was done with the "magnet comparator" which is a movable stainless steel structure supporting 4 displacement sensors and a clinometer.

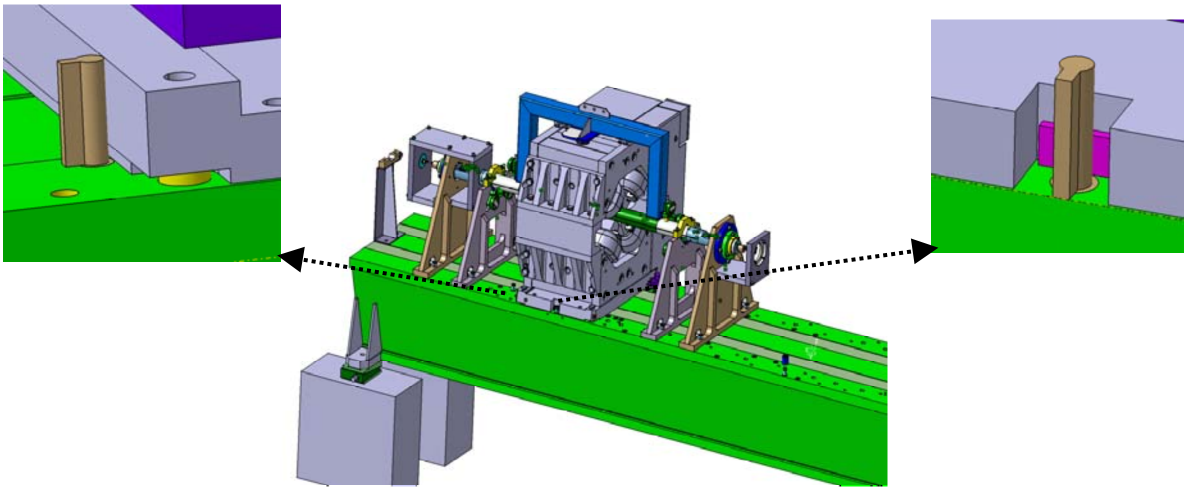
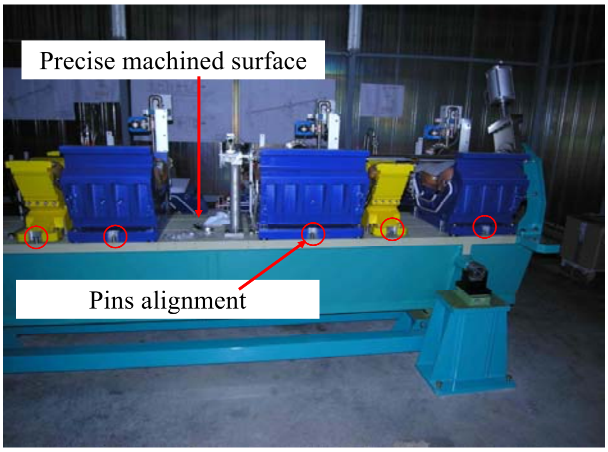


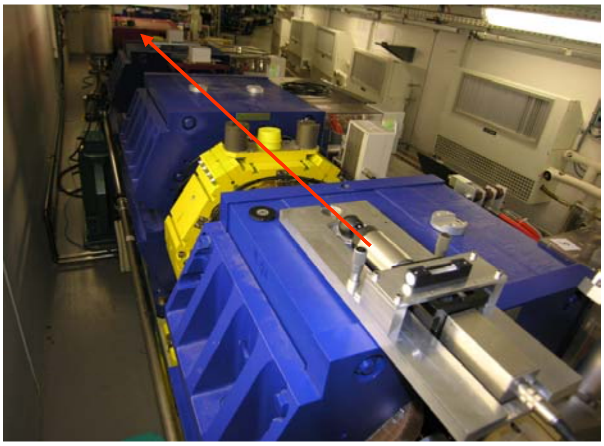
Fig.2 : The BMS with a Qpole, shims & the "magnet comparator"

3.3. Mounting the magnet on the girders *(3), (3')*

An alignment checking campaign of the magnets on their girder has been held in an area especially dedicated to the mounting operations *(3)*. The magnet survey is realized by means of a STR500 laser for horizontal and vertical ecartometry and with a Nivel20 clinometer for tilt measurements. Since the survey stays on the monuments and not on the magnetic centres themselves, we must use the offsets coming from the "magnet comparator" to link them together. Finally, a least square straight line is calculated with the magnetic centers location resulting from the survey: it is considered as the magnetic axis of the girder that will be positioned on the theoretical orbit of the storage ring.

This checking procedure is repeated inside the tunnel after the whole mounting of the ring *(3')*. We took advantage of that operation to survey the BPM located on the girders and the ones fixed on the floor at both ends of the straight sections.





Figs.3 & 4: Mounting the Qpoles & STR500

3.4. Positioning the Qpoles with respect to the nominal orbit *(4)*

A standard and classic procedure has been applied for the last step. Fig.6 sums up the whole operation: a survey allows the ring shape and 3D parameters calculations (6 degrees of freedom, DOF). Then, the adjustment of each girder is managed by means of 5 movable displacement sensors controlled by computer inside an Excel sheet. All the movements are done manually. A second survey is necessary to check the adjustment quality.

The planimetric surveys concern the totality of the Qpoles, even if they are 3 or 4 on the same girder: it allows a good redundancy for the girder positioning. They are done with two TDA5005 total stations whose EDM is calibrated by ESRF calibration bench. In addition, wire ecartometry measurements concerning the totality of the Qpoles complete the survey. Every girder is linked to its adjacent ones by direct ecartometry measurements on the whole circumference of the ring.

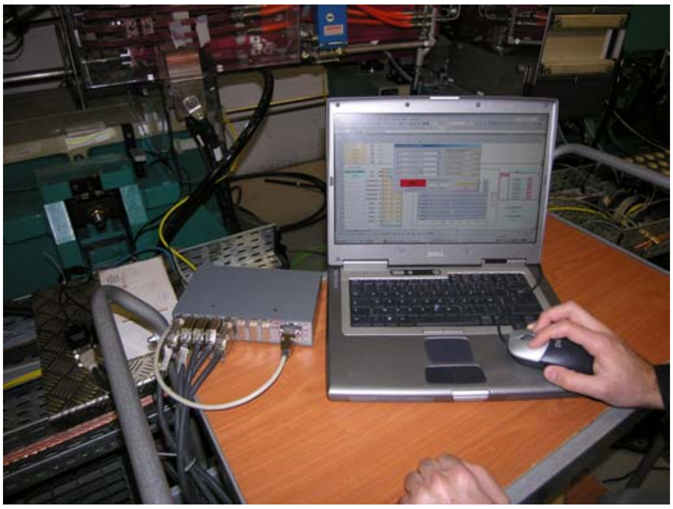


Fig.5 : Excel data sheet for managing the sensors

The least square calculation of the bundle adjustment includes also the STR500 ecartometry of the Qpoles on the same girder. The Matlab soft developed at SOLEIL uses the SVD algorithm that allows a full free adjustment of the network. The Excel data sheet (fig.5) used in the tunnel to manage the girder displacements calculates online the sensor readings corresponding to the correction displacements (translations & rotations) at each step of the girder adjustment. The adjustment phase fully separates cinematic and metrology chains (resp. jacks & sensors). It allows limiting the backlash and the negative effect of the clamping on the girder adjustment.

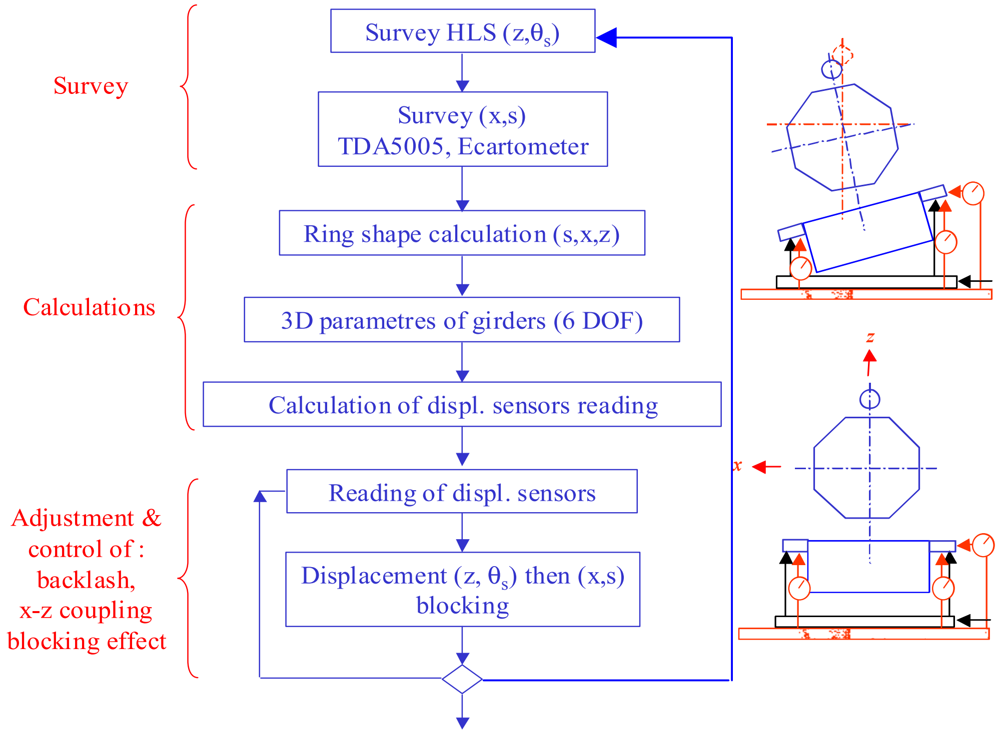


Fig.6 : Positioning the Qpoles MC on the orbit

4. THE STABILITY TIME CONSTANT

4.1. Definition

The field of instrumentation needs certain precautions concerning the stability of the used instruments and also of the object to be measured itself. In other words, stability analysis is obligatory when measuring tight offset or displacements: the instrument stability must be compatible with the required measurement accuracy. That idea is not a new one, every metrologist has been confronted to that problem. We propose to formalize this, with the concept of Stability Time Constant (STC).

The Stability Time Constant (STC) is defined as the delay δt during which one wants less than a certain quantity δd of parasitic (randomly or not) drift whatever its origin (mechanics, optics, electronics, etc.):

$$STC = (\delta d, \delta t)$$

That tool helps the stability analysis of measurement methods including any kind of mounting system (mechanics, optics, electronics, etc.). The right measurement condition will be achieved if:

$$\delta d \ll \delta m \text{ during } \delta t$$

The main interest of that concept is to keep in mind stability analysis at any step of a design or measurement procedure. The STC can be inserted in error budgets of a measurement procedure.

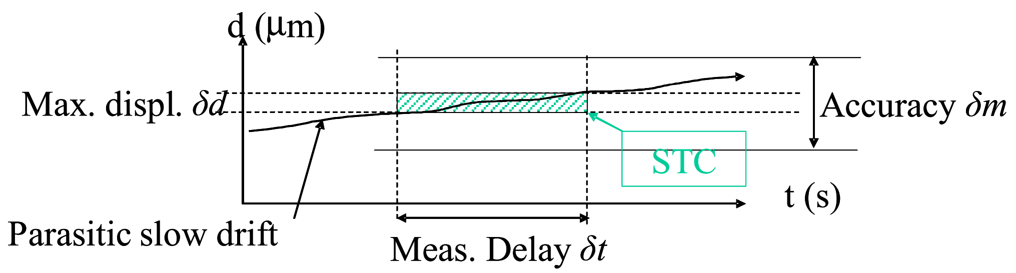


Fig.7: STC in the case of a measurement system affected by slow drift

The following tables give examples of STC applications in the instrumentation field:

Ecartometry on a 3-4 m base with:	STC	Remark
STR500 laser	(few µm,10mn)	delicate
STR500 laser	(few µm, 2mn)	easy
Wire ecartometer	(few µm, 10mn)	easy

Long term tilt measurement (θs):	STC	Remark
Movable clinometer	(few µrad , 30s)	easy (rotation)
fixed clinometer	(few µrad, ∞)	difficult

TDA5005 measurement (θz):	STC	Remark
	(few µrad , 5mn,)	easy/delicate
	(few µrad , 1h)	difficult

Pillars of a geodetic network (≈ ground stability):	STC	Remark
as (X,Y) absolute reference	(few 0.1mm , ∞)	difficult
as (X,Y) intermediate point	(few 0.01mm , 1 day)	easy

4.2. STC and measurements on the BMS *(1)*

Since the Qpoles set on the same girder are measured by the BMS during a delay within two days, the mechanical path of the bench, i.e. from the coil to the upper plane and the X pin, must have a STC = (few µm, 2 days). That condition is easy to obtain because a reasonable delay has been chosen. In the case where the Qpoles should have been either randomly distributed or sorted all along the storage ring after having been all measured on the BMS, the bench STC should have been (few µm, 3 months). That last value is delicate to obtain, because of the slow deformations of bench or the regular chocks of the magnets that wear and tear the bench reference surfaces during the STC delay.

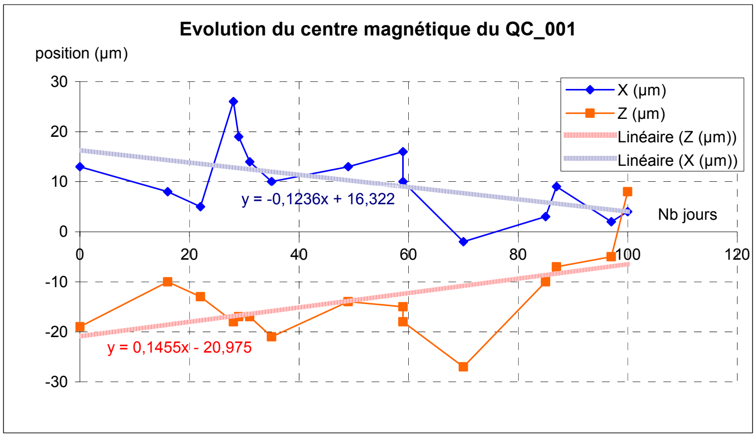


Fig.8 : Periodic magnetic checking of the BMS with a reference

Bench STC can be extrapolated by using its periodic survey with the same reference Qpole shown in fig.8 [2]. The magnet comparator has the following STC (according to the DOF), including its mechanical and electronic (sensors) stabilities:

X	(few µm , 5mn)	rotation of the system
Z	(few µm , 3 months)	no rotation possible
θs	(few µm , 5mn)	rotation of the system

The Z measurement needs to be calibrated regularly (δT) with a simple and stable bench. In that case the STC is (few mm , δT). The electronic reference of the four displacement sensors needs to be linked to the mechanical structure at each use of the comparator (calibration shim). We have observed a Z stability of the measurements of approximately (5µm, 3 months).

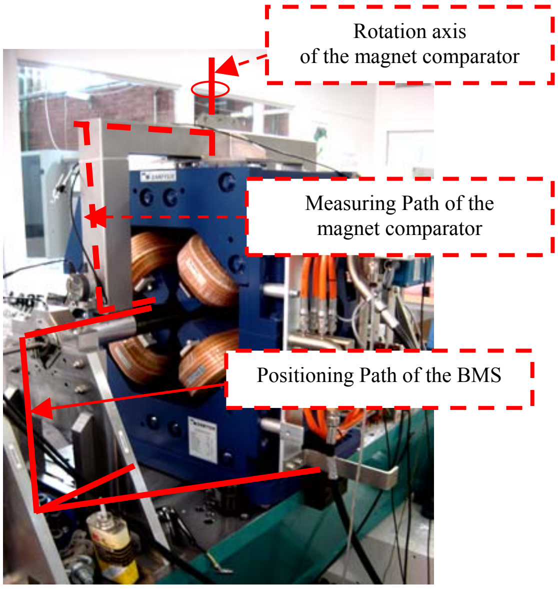


Fig.9 : Magnet comparator & BMS

4.3. STC and measurement checking on the girder *(3), (3')*

The checking operation of the Qpoles on their girder does not present major problems in terms of stability (one will not take into account the long term relaxation due to the girder machining). The only one precaution is to work with a good thermal stability inside the mounting area. The girder must be perfectly link to the floor during the check since the gravity reference is used with only one Nivel20 clinometre (STC: (1µrad, 10mn)). Otherwise, if the girder may be affected by displacements during the measuring phase, differential measurement with a reference Nivel20 fixed to the girder is necessary to reach the same STC.

The measurement procedure needs a STC analysis of the instruments:

STR500 laser for X,Z ecartometry	(few µm, 2mn)	differential & fast measurements
Nivel20 for θs	(few µrad, 1mn)	rotation of the clinometre

4.4. STC and positioning the Qpoles on the orbit *(4)*

It is obvious that the thermal stability of the whole tunnel is the first condition to be required in order to work properly. A complete campaign of survey & adjustment may take several weeks (depending on the manpower). The condition to be respected is that this working delay cannot allow to the machine to move significantly.

The planimetry is realized by means of two LEICA TDA5005 total stations and a wire ecartometre. That last instrument has been designed for SOLEIL by the company SYMETRIE, Nîmes, France. The achieved results in terms of straightness measurements seem to confirm its excellent quality. The set, wire detection / optical ruler reading, is in the range of 10µm accuracy.

The corresponding STCs are:

TDA5005 measurement (θz)	(few µrad, 10mn)	horizontal angle meas.
Wire ecartometer (X)	(few µm, 10mn)	wire stability per alignment

The HLS network is now used as the absolute altimetry of the Qpoles through the girder where they are fixed. One can use STC for different aspects of the HLS stability. Since the free surface of the water is the horizontal reference of HLS measurements, it is important to estimate the corresponding STC. Several tests were held in that way [4]. They gave $STC_w \approx$ (±7µm , 3h).

The stability of the electronics is a fundamental question since its ideal STC should be $STC_{elec} \approx$ (few µm, ∞) whatever the use of the HLS (relative or absolute). The electronics must not drift, even very slowly and it has to be proved. A long term stability test held at Soleil from 2004 to 2005 [3]. It gave a STC of rougthly (10µm, 1 year). These figures are encouraging. But that achievement cannot be extrapolated to many years. Consequently, the decision to apply the following strategy has been taken, in order to use the HLS network in good conditions: periodically: we store each HLS reading when set on a stainless steel calibration block [4]. Since that calibration holds inside the tunnel, the whole real measurement channel of every sensor is integrated. With that method, we estimate that the STC is controlled to approximately (2µm, 6 months).

4.5. STC general considerations

Actually, the stability of the electronics concerns the entire instrumentation field. STR500 laser, Nivel20 for instance, may be affected by slow drift. More generally, the totality of instrumentation is concerned, whatever the origin of the instability (electronics, supporting mechanics, etc.). That's why every user has to regularly (δT) calibrate his instruments to keep its accuracy (Acc). The corresponding STC is then (δT, Acc).

Many other methods allow reducing the STC. Here are the main ones we apply as soon as we can do:

Short delay for the measurements:

STR500, wire ecartometer, clinometers, theodolite angle measurements,

Rotation of the instrument:

Clinometers, magnet comparator.

Fixed calibration block:

Displacement sensors on magnet comparator, HLS.

Tight range of measurements coupled to differential measurements :

STR500, displacement sensors of the magnet comparator, ecartometry related to any reference straight line (i.e. without centering on known points).

5. ACHIEVED RESULTS & CORRESPONDING ERROR BUDGETS

Studies had been realized in order to estimate the accuracies one could expect for the storage ring alignment [1]. We now present the *a posteriori* standard deviation, coming from the measurements realized on the magnetic bench and on the storage ring girders. The results are either better or a little bit worth than expected. In both cases, it is interesting to try to estimate the intermediate steps that could lead to the real measured accuracy.

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:

$\sigma^2 = \sum_{i=1}^{n} \sigma_i^2$ for n random errors.

5.1. Positioning path (blue line from *(1)* to *(3)*)

The planimetric error budget takes into account (fig.1 & 10): the measurements realized on the magnetic bench leading to the shim thickness, and the machining quality of the girder. Therefore the magnet comparator measurements do not appear in that error budget. We want here, to qualify the Qpole magnetic centers alignment on a girder (positioning path from *(1)* to *(3)* on fig.1). The concerned parameters are as follows: repeatability of the magnetic measurement, stability of the bench itself, quality of the shim realization, repeatability of the upper yoke positioning (because it has been dismounted to install the vacuum chamber inside the tunnel), thermal uncertainty and quality of the mechanical references machining of the girder. In this error budget, we use *a priori* standard deviations for intermediate steps as the upper yoke repositioning, the thermal effects or the X-Z coupling due to the girder residual twist. The other terms come from better known error sources: the bench stability has roughly STC (3µm, 2 days), measured by the Magnetic group, the shim dispersion comes from the BMS team and the repeatability of the magnetic centre detection ($\sigma \approx 3$µm) is based on the Magnetic group experience. The quality of the reference pins realisation on the girder has been measured by the Alignment group. The *a priori* accuracy of the Qpoles alignment on the girders was estimated to 25µm [1] at the design phase (Avant-Projet Détaillé).

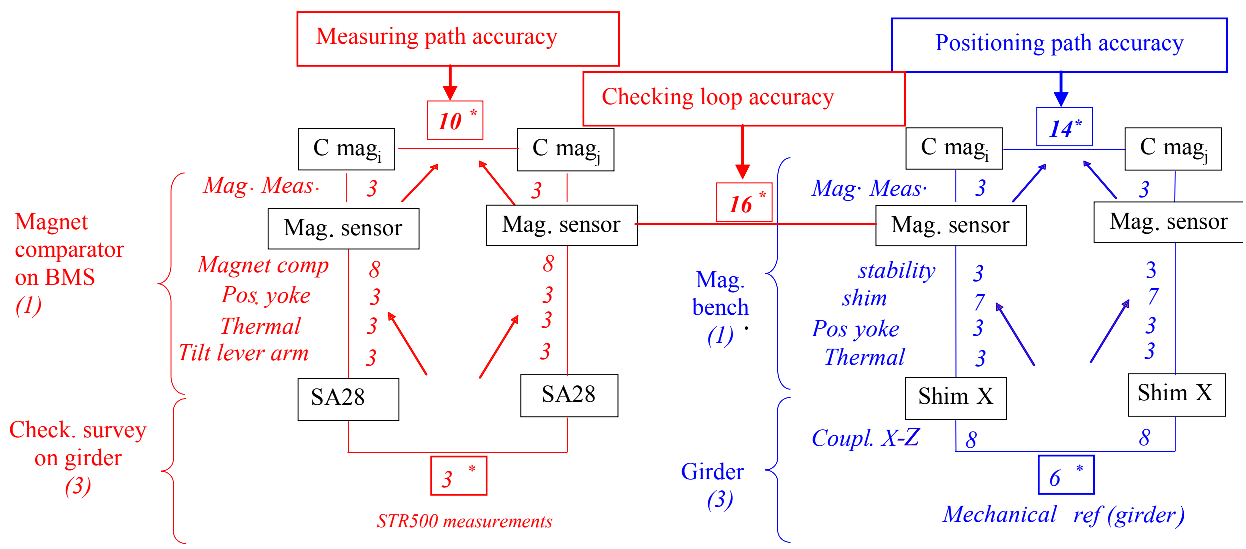


Fig.10: Error budget of measuring & positioning paths

The checking loop accuracy appears between both

5.2. Measuring path (red line from *(1)* to *(3)*)

The path includes the "magnet comparator" measurements from the coil to the survey monument (called SA28) of the Qpole (fig.1 & 10). The corresponding accuracy is estimated to 8µm, including the STC. One can reasonably add several terms as thermal effect and yoke repositioning. Then, all the SA28 are linked with STR500 & Nivel20 clinometer with 3µm accuracy for both. The checking loop presents 16µm accuracy on the fig.10, which is quite similar to the 15µm value we really achieved. It is important to notice that the checking loop does not concern the girders with only two Qpoles since in that case, two points are necessarily "aligned ". That case corresponds to 20% of the girders at SOLEIL.

5.3. Planimetric errors budget for the Qpole MC alignment on the orbit *(5)*

The full machine alignment procedure needs typically a first survey, followed by the adjustment of the 56 girders, and finally a second survey for checking. Unfortunately, up to now, we couldn't have this ideal plan. Therefore, the measured standard deviation we present, gives the actual state of the machine in terms of alignment, really seen by the beam itself but may not correspond to the ultimate accuracy of the method.

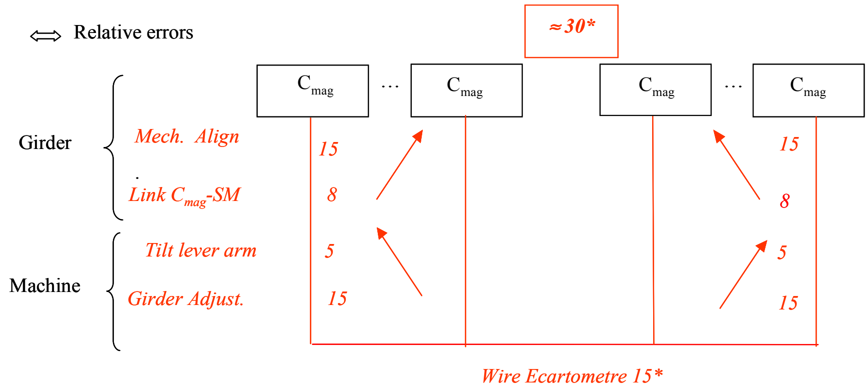


Fig.11: Error budget of local alignment (smoothing)

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. We have improved the error budget in comparison to the initial one since we better know some terms: mechanical alignment on a girder (see previous chapter), coupling X-Z (tilt measurement of the girder inside the tunnel) and the magnet comparator measurements that link survey monument to magnetic center. It has to be noticed that the relative errors coming from the bundle adjustment are similar to the wire ecartometry *a priori* error.

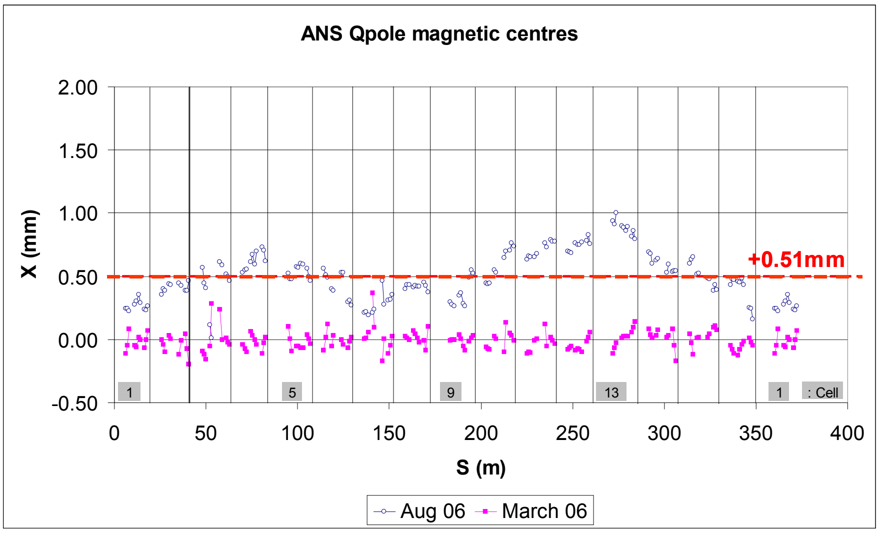


Fig.12: General shape of the storage ring

The general shape of the storage ring is presented on Fig.12. The error budget of such a survey may be linked to the absolute errors calculated by the bundle free adjustment. We noticed at the IWAA2004 [1] that these errors seam a little bit optimistic (<0.1mm). Nevertheless the low frequencies observed on that chart including the average value, can be considered as significant. The curve dating of August is centered on +0.51mm, that corresponds to a $\partial ø$ = +1.0mm for the diameter and ∂c=3.2mm for the circumference. It is true that this value is closed to the one given by the RF frequency measured by the physicists 2 weeks later ($\partial ø$ = +1.4mm ⇔ ∂c=4.5mm), but we do not fully explain the offset related to the nominal value. Nevertheless, the present circumference is fully compatible with the RF frequency adjustment range of both booster and storage ring.

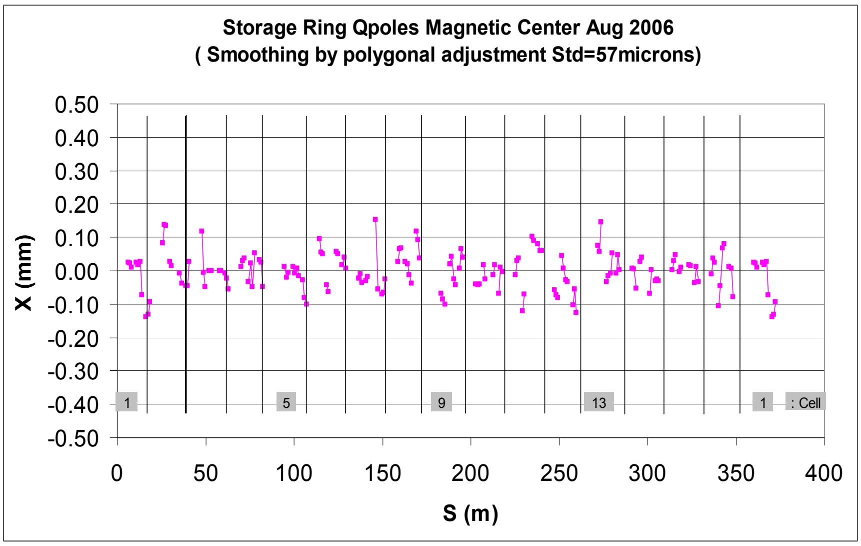


Fig.13: Local alignment of the storage ring

Fig.13 shows the state of the storage ring in terms of local alignment (polygonal smoothing: least square adjustment polygone, the dipole nominal angles being preserved) 5 months after the adjustment of the girders. The standard deviation is σ = 57µm. That value is twice the one expected. We do not have sure explanation: either the machine has slightly dispersed in alignment after 5 months, or the error budget does not correspond to reality, probably both. More investigations are planned for the next year.

The table 1 collects the achieved results of both planimetry and altimetry. More details about the altimetric alignment by means of HLS are presented in the IWAA 2006 [4]. One can just remark that there is another measuring path coming from the Qpole MC to the HLS sensor in order to align the Qpoles on the nominal orbit in an absolute way.

Table 1: 1σ values for measurement accuracies and achieved results on Qpole MC alignments

	Expected		**State on Aug 06**	
	σ_X (µm)	**σ_Z (µm)**	**σ_X (µm)**	**σ_Z (µm)**
Magnet comparator			8	5
STR500+Nivel20			5	5
TDA5005 dist. (Bundle Adjustment)			σ_{dis}=0.11mm	
TDA5005 angles (BA)			σ_α=6.10^{-4} deg	
Wire ecartometer (BA)			σ_{eca}=11µm	
Qpoles MC on girder	20	20	15	11
Qpoles MC on orbit (smoothing)	50-100	50-100	57	63
Qpoles MC on orbit (absolute) ∂d	±0.25mm		+1.0mm	

6. CONCLUSION

The SOLEIL storage ring has been running for almost two month and machine physicists seem to be very satisfied of its alignment since they obtained several turns of the storage ring without any beam correction and without the use of the RF cavity or the sextupoles at the occasion of the very first tests. In addition, the estimation of the error budgets we present appear as being reliable since the beam natural vertical envelope without any corrector leads to an estimation of the alignment by means of the BETA model to 20µm for the Qpole magnetic center on the girders and to 50µm for the girders [5]. It has to be compared with respectively 15µm and 60µm noticed previously. However, the ultimate accuracy of girder alignment has not been yet obtained. That will be the primary goal of the next year.

Acknowledgments

That achievement shows the excellent work of both, girder machining and magnetic measurements directed by other SOLEIL teams: Conception/Iingénierie, and Magnétisme/Insertion groups.

Such results could not be reached in so short delay regarding the size of the Aligment/Metrology Group (AMG: 5+1 persons), without the help of the SOLEIL Mechanical team who has been pre-aligned the whole SR in the mm accuracy, thus favoring the fine alignment of the girders by the AMG.

References

[1] A. Lestrade “Principles & status of SOLEIL Alignment System”, IWAA'08, CERN, November 2004.

[2] A. Madur “Bilan des mesures magnétiques concernant les défauts des quadrupôles de la poutre ANS C15-P1”, communication privée, Synchrotron SOLEIL, September 2005.

[3] A. Lestrade, M. Ros “qualification tests of the SOLEIL storage ring HLS”, IWAA'08, CERN, November 2004.

[4] A. Lestrade C. Bourgoin, E. Guigné, M. Jagu (ATGT), M. Ros, M. Sebdaoui “THE HLS Used as an Absolute Reference for the Alignment of the SOLEIL Storage Ring”, IWAA'09, SLAC, September 2006.

[5] A. Nadji, communication privée, Synchrotron SOLEIL, September 2005.