OVERVIEW OF THE STATUS OF THE SOLEIL PROJECT

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Abstract

SOLEIL is a third generation Synchrotron radiation Source, under construction in France near Paris. The Storage Ring consists in a 354 m circumference ring, with 16 cells and 24 straight sections, out of which up to 21 will house Insertion Devices (ID). The optics features a low 3.7 nm.rad emittance at the 2.75 GeV operating energy, so as to provide high brilliance, from the VUV up to the hard X ray domain. In order to reach a long beam lifetime, and beam position stabilities in the micron range, significant attention was paid at each design stage (optics, magnets, beam position monitors, vacuum and RF systems,..), including on the design of the building, the construction of which is now complete. This resulted in some unprecedented approaches such as the intensive use of NEG coating vessels, or the development of a dedicated SC RF cavity and of 200 kW solid state RF amplifiers. The injector system (100 MeV Linac) and the 3 Hz full energy Booster synchrotron have reached nominal operating conditions by fall 2005, while the ring commissioning started in May 2006. Innovative ID's were designed and built so as to provide the best possible performances in a wide energy range (5 eV to 50 keV).

INTRODUCTION

SOLEIL has been designed as a low emittance synchrotron radiation source with a modified Chassman Green optics accommodating a total of 162 m of straight sections [1], allowing a large number of insertion devices to be installed. With a 500 mA beam current target, the average brilliance will range from 10^{16} ph/s/0.1% BW/mm^2/mrad^2 for the bending magnets sources up to 10^{18}-10^{20} ph/s/0.1% BW/mm^2/mrad^2 for the insertion devices. The construction of the buildings started in August 2003, all the major components were ordered before June 2004 and further characterized. The installation of the components of the storage ring, including the first four insertion devices, was completed in May 2006. The progress of the commissioning of SOLEIL is here described, with the first 100 MeV LINAC beam in July 2005, the ramping up to the nominal 2.75 GeV energy in the booster, and the successful and fast storing of electrons into the storage ring.

LINAC AND BOOSTER OPERATION

The **HELIOS** 100 MeV LINAC has been built by THALES and makes use of 2 accelerating sections donated by CERN [2]. The transfer line from the Linac to the Booster was built by SOLEIL. Its diagnostics enabled to fully characterize the Linac beam performances [3]. The first 100 MeV beam was produced on the first trial, on July 2nd,2005 and was used to validate the radiological protections of the LINAC and Booster tunnels. In the Long Pulse Mode the LINAC produces a 300 ns train of pulses modulated at 352MHz with a total charge of 9.3nC for a specified maximum value of 8nC. The energy spread is below ±0.5% thanks to the so-called "beam loading compensation" technique which consists in injecting beam during the filling time of the 2nd accelerating section. The measured emittances are 47 (±10) π mm.mrad in the H plane and 52 (±10) π mm.mrad in the V one, i.e. 4 times below the specifications. In the "Short Pulse Mode" for the temporal structure, the LINAC provides 1 to 4 pulses of 1.3 ns (required value < 2 ns). The measured current for 1 pulse is 0.52 nC and 2.15 nC for 4 pulses (specification: 0.5 nC per pulse). Energy spread is ±0.58% for 1 pulse and ±0.82% for 4 pulses.

The 157 m long **Booster synchrotron** was designed to accelerate the 100 MeV Beam from the Linac up to the 2.75 GeV nominal energy of the storage ring and features a 150 nm.rad horizontal emittance at 2.75 GeV [4]. The magnets, arranged in a FODO lattice are ramped at 3 Hz, using 'SLS' type digitally controlled power supplies [5]. All pulsed magnetic equipment (septum magnets, kickers) were designed in house and their pulsers make use of solid state switches (**MOS** for the HV Booster kickers and IGBT's for HV SR kickers)[6]. A very flexible synchronization system enables to vary at will the filling pattern and injection frequency.

The first injection was tried on July 23rd,2005 and rapidly the 100 MeV beam was stored for up to 2 million turns. With proper correction of the chromaticity, improvement of the synchronisation and transfer line adaptation, the injection efficiency reached 80%. The first energy ramping was achieved at 2.75 GeV on October 13th, 2005. After further tuning, the Booster efficiency now reaches 94%, and when the beam is not extracted, it is kept running during the deceleration down to below 150 MeV. This demonstrates an excellent tracking between dipoles and quadrupole power supplies which enables to control the tunes all along the 3 Hz cycle. Extraction from the Booster was performed very easily on May 8th, 2006, and the beam was guided along the transfer line up to the injection point of the storage ring.

STORAGE RING MAIN COMPONENTS

The storage ring main parameters are shown in Table 1. To reach the best performances expected from a 3rd generation source, special efforts were brought on all equipment to achieve the sometime very demanding specifications that were targeted.

TABLE 1. SOLEIL Storage Ring Main Characteristics		
Nominal energy	GeV	2.75
Circumference	m	354.097
Revolution period/frequency	µs/MHz	1.18/0.846
Number of cells/ of super-periods		16/4
Number of long (12 m), medium (7m) short (3.8 m) straight sections		4, 12, 8
Betatron tunes ν_x ; ν_z		18.2 ; 10.3
Momentum compaction (α_1, α_2)		$4.38\ 10^{-4}$/ $4.49\ 10^{-3}$
Relative Energy spread		$1.016\ 10^{-3}$
Damping time (longitudinal, transverse)	ms	3.27/ 6.56
Emittance (horizontal, vertical assuming 1% coupling)	nm.rad	3.74 / .037
Total radiation power loss for 500 mA, with ID's	kW	575
Bunch length	ps	13.8
RF frequency	MHz	352.2

During the magnetic measurement campaign, from May 2004 to August 2005, the **326 magnets** of the Storage Ring have been characterized in terms of magnetic axis centering and field properties [7]. For the dipoles (built by TESLA), two types of measurements have been performed at SOLEIL: field mapping in the mid plan using a Hall probes bench, and field integral comparison with a reference magnet using a stretched wire bench built by SOLEIL. For the 164 quadrupoles (built by DANFYSIK), a rotating coil bench has been built and optimised at SOLEIL in order to reach magnetic centre and tilt angle adjustments within ± 25 µm and ± 0.1 mrad respectively. The results are excellent thanks to the sensor quality and the very great care taken by people during measurements. The RMS values are of the order of the measurement reproducibility. For the 124 sextupoles (built and measured by SIGMAPHI), the results are within tolerances. Statistical analysis of measurements is given in Table 2.

Table 2	**Beam center positioning (after shimming)**			
	Quadrupoles		Sextupoles	
	Mean Value	RMS value	Mean Value	RMS value
ΔX (microns)	1.5	8.4	-3	15
ΔZ (microns)	2.6	7.5	2	10
Tilt (mrad)	0.008	0.040	0.010	0.100

A sorting code was developed to optimize the position of each dipole in the ring in order to reduce the predicted maximum horizontal closed orbit distortion from 1.5mm before the sorting to 0.35mm after the sorting.

All SR **power supplies** are digitally regulated. Hazemeyer has produced the power supplies for the Dipoles (1) the Quadrupoles (160) and Sextupoles (10). The 144 Corrector power supplies have been built by Bruker. All **pulsed magnetic equipment** (septum magnets, kickers) were designed in house, in particular the Eddy current septum magnet on which a very effective magnetic shield enabled to reduce the stray field seen by the stored beam down to 10 ppm of the main field [8], which is crucial for top-up injection.

The **Vacuum system** is a key issue of SOLEIL. The 2.5 m long stainless steel dipole vacuum chambers have been manufactured with very tight tolerances (± 0.5 mm) by SDMS (France). An all aluminium (Al) solution with Non Evaporable Getter (NEG) coating has been adopted for the quadrupole vacuum chambers. They have been fabricated by SDMS before delivery to SAES Getter (Italy) which performed the NEG deposition. The NEG requires in-situ bake-out to 180°C to be activated but is expected to reduce significantly both the dynamic pressure and the photon desorption yield, thus resulting in a shorter conditioning time. With up to 56 % of the ring circumference equipped with NEG coated Al vessels (i.e. almost 200 m), SOLEIL is the first storage ring to make such an extensive use of this technique. Ten low aperture (10 mm inner height) ID vacuum vessels (again in Al with NEG coating) were already installed in the medium straight sections of the ring, as well as a very long (10.5m, 14 mm inner height) ID vacuum vessel, before the start of the commissioning.

Special care was devoted to the longitudinal stability of the electron beam, so superconducting technology was adopted for the **RF cavities**. Two cryomodules, each containing a pair of superconducting cavities are required to provide the maximum power of 600 kW needed at 500 mA. The first cryomodule, was specifically designed by the CEA and CERN, was tested on the ESRF Storage Ring in 2002, was then refurbished and finally tested at CERN : Its performances exceed the requirements for the SOLEIL normal operation: 150 kW per coupler and 1.5 MV per cavity. It was installed on the ring in November 2005, cooled down and RF conditioned in May 2006 and will, alone, enable operation up to 300 mA [9]. A second cryomodule, being built by ACCEL will allow reaching 500 mA in 2007.

Each of the four cavities is powered by a **190 kW solid state amplifier** consisting in a combination of four "towers" producing about 50 kW each. The solid state amplifiers, technology specifically developed at SOLEIL, combine the RF power amplified by a large number of 315 W elementary modules (150 for the booster amplifier and four sets of 180 ones for each 190 kW storage ring amplifier). A first step was reached in 2004 with the operation in CW of the 35 kW-352 MHz solid state amplifier of the booster. In April 2006, the two amplifiers of the storage ring were able to deliver 180 kW to a dummy load. They are now running very smoothly powering the 2 cavities during the SR commissioning.

Many **diagnostics** were installed on the ring, such as a visible light monitor, a pinhole camera to measure the emittances, H and V scrapers, current monitors (FCT and DCCT's), a shaker and striplines to measure the tunes, beam loss monitors, and a streak camera. 120 Beam Position Monitors are distributed along the ring and with the LIBERA electronic modules (from Instrumentation Technologies) will enable to control the electron orbits with a sub-micron resolution. Turn-by-turn reading of the BPM was used efficiently from the first day of the commissioning [10].

During the design phase of the different SR equipment, the possible contribution of each component (BPMs, tapers, dipole slot, striplines, scrapers,.. including the impact of the NEG coating) to the **ring impedance** was carefully looked at, and a full comprehensive model was built [11]. Simulations have shown that the instability threshold associated to the resistive wall is expected to appear above 30 mA in uniform filling.

Each **Front-Ends** includes, a fixed absorber, a photon shutter, moveable diaphragms, an acoustic delay line and a Gamma stopper. The design is rather compact. The installation of 12 front-ends is almost complete.

The **machine control system** is based on TANGO [12]. At the field level, the machine control system is composed of three kinds of hardware components: Programmable Logic Controllers from SIEMENS, for slow and asynchronous processes, using Profibus, Compact PCI crates for fast acquisition and asynchronous processes. Standalone motion controllers will manage stepper motors as well as DC or piezo ones.

All these components are now connected to the higher level - operator consoles, process and archiving servers - via a switched Ethernet network (1Gb/s and ultimately 10Gb/s) dedicated to the machine control system. The TANGO software has been selected as control-oriented CORBA framework. Basic functionalities, such as generic high level applications for system configuration and monitoring of the values and bindings to development tools like Matlab, Labview and Python, are available. GlobalScreen (software tool from ORDINAL) providing Supervision Control and Data Acquisition is interfaced to TANGO. For the commissioning [13], the Matlab Middle Layer tool was adapted to communicate with the TANGO world. TANGO implemented for the first time to such a large scale has fully demonstrated its efficiency during the beam commissioning of the storage ring.

AIMING AT BEST POSSIBLE STABILITY

Significant efforts have been made, at the design stage to minimize all possible contributions to beam position instabilities. In order to guarantee long term stability, the temperatures of the water cooling circuit and of the air conditioning inside the SR tunnel are regulated at 21.0 ±0.1°C, whilst the temperature in the experimental hall is regulated at 21.0 ±1.0°C. The synchrotron building was designed so as to minimize the transmission and amplification of vibrations: The very thick storage ring and experimental hall slabs (95 cm and 75 cm respectively) are lying on 600 piles, 15m deep, whilst the other parts of the building (metallic frame supporting the roof and the cranes, technical rooms, labs, circulation path) are resting directly on the ground. This provides an excellent decoupling between the "noble" areas and the place where vibrations could be generated, as can be seen on figure 1, which shows that during a crane motion, the induced vibration at the SR slab level is well below 1 µm, and at frequencies below 20Hz.

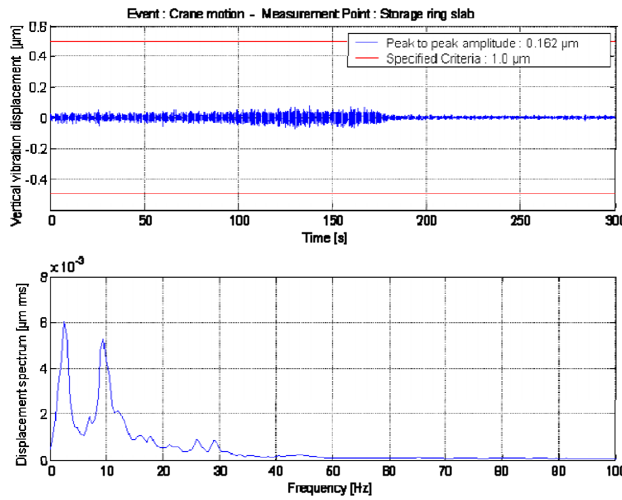

Fig.1: Vibrations induced on the SR slab during crane motion.

The girders supporting the magnets were optimised so as to push the first eigen modes of vibration towards high frequencies. They are made of very massive supporting beams strongly clamped onto the SR slab. The dipole magnets are sitting on 2 adjacent girders. As a result, the first eigen mode of the girder appears at 45 Hz, i.e. quite far away from the frequency domain that can be amplified by the slab. This excellent result is illustrated on figure 2 which shows the displacement spectral density as measured on a quadrupole in its final environment inside the tunnel with all cablings and water connections.

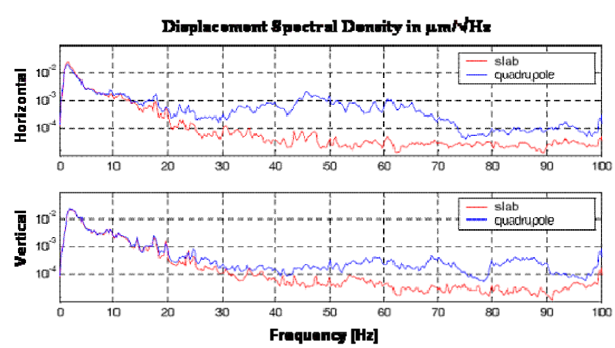

Fig.2: Displacement spectral density recorded on a SR quadrupole magnet after final installation in the tunnel.

The BPM blocks are fixed by strong supports on the girders and are the fixed points of the vacuum vessels. They are kept at constant temperature by water cooling at 21°C.

COMMISSIONING OF THE RING

The installation of the components of the storage ring, including the first four insertion devices, was completed in May 2006 [14]. On May 14th, 2006, the beam could be circulated for the first time up to 3 turns without any corrections, with beam settings close to the theoretical values [15]. Its trajectory was followed using the turn-by-turn mode of the Beam Position Monitors (BPM) and synchrotron radiation could be observed on a CCD camera on the diagnostics hutch.

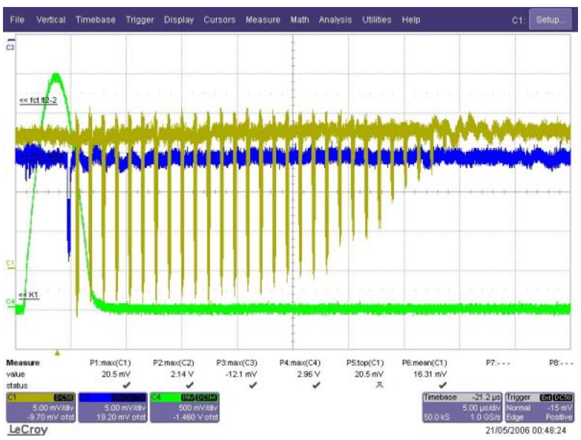

Fig. 3: successive turns detected by the FCT without RF and with sextupoles OFF.

As shown on figure 3, the beam goes several times through the 10 mm small vertical aperture of the 10 insertion device chambers distributed along the ring.

Such a result underlines the quality of the alignment of all the equipment (magnets, girders, and vacuum vessels) and of the magnetic measurements of the electro-magnets, which was later confirmed by the measurement of the uncorrected closed orbit (rmsH=2.3 mm, rmsV= 0.4 mm).

Before attempting to store a beam, radiation measurements were performed all around the Storage Ring tunnel to assess the shielding efficiency. Once these controls were completed, it was then possible to continue the commissioning during normal working hours with people working for the beamline construction in the Experimental Hall.

After completion of the RF conditioning of the super conducting cavities, and vacuum bakeout of the last vacuum vessels, a three week uninterrupted period was scheduled to perform the first commissioning tests. In fact, due to some difficulties with the water cooling circuits (some small resin balls from the deionisation plant were accidentally spread into the whole circuit, blocking some filters or some cooling channels), the total time available for beam test was reduced to ~14 days.

The first trial to store beam started on Friday June 1st and after having fixed some equipment failures, a first beam (0.3 mA) was stored on June 2nd at 2 am. The first accumulation (up to 8 mA) was performed on June 4th at 3 am. The increase of the stored current progressed rapidly: 15 mA on June 6th, 30 mA on June 10th, 50 mA on June 15th, 70 mA on June 18th. The integrated current reached 2.7 A.h at the end of the run, on June 19th, as shown on figure 4 below.

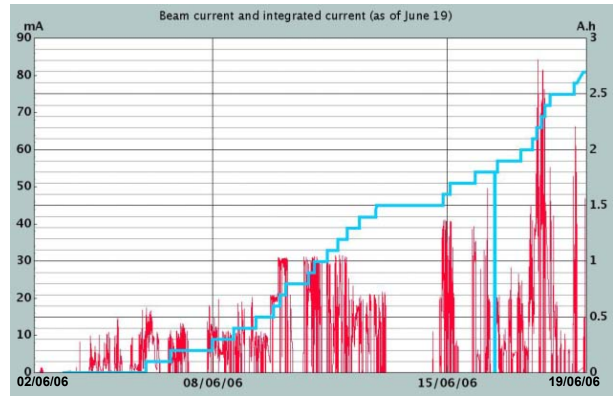

Fig.4: Beam current (red) and evolution of the integrated current (blue) during the 3 week run.

Considering the rather small integrated dose achieved so far, the conditioning of the vacuum vessels progressed quite well, with a reduction by almost a factor 10 on the normalized dynamic pressure (P/I) as shown on figure 5.

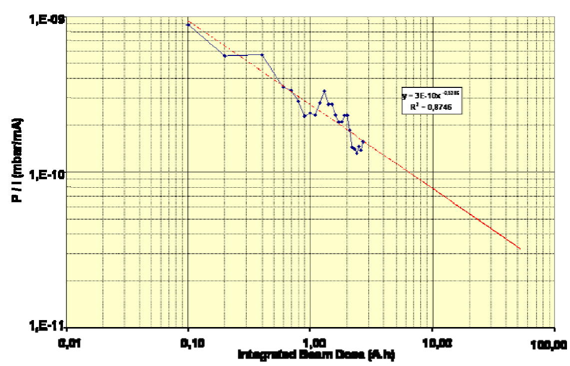

Fig.5: Average pressure of Cell C07 normalised to current vs integrated beam dose.

This good result clearly demonstrates the beneficial effect of the NEG coating on the aluminium chamber. It should be further confirmed when increasing the integrated dose.

At the present stage, some saturation was observed, at time, when increasing the current, which seems to be due to the so-called fast ion beam instabilities. The signature of resistive wall instabilities could be observed in uniform filling at about the predicted threshold [11], but could be easily overcome with a positive chromaticity.

INSERTION DEVICES

SOLEIL, thanks to the high straight section length over total length ratio, can accommodate up to 24 insertion devices for 21 beamlines. The energy range covered by the SOLEIL Insertion devices extends from the UV to VUV, soft and hard X ray range, following a shortening of the period length. The first four undulators, HU640, HU256, H80, U20* were already installed before the start of the commissioning and did not lead to specific

* The number refers to the magnetic period in mm

difficulties. Magnetic design [16] was carried out and optimized using RADIA and SRW. The predicted effects of the ID's on the stored electron beam were computed with the codes BETA and TRACY2, leading to tolerances regarding field integral, trajectory and high orders harmonics of magnetic fields for each specific device. The magnetic measurement laboratory is equipped with two ESRF benches with Hall probes and rotating coil, a specific long bench with coil and Hall probe for the 10 m long HU640 and a BINP Hall probe and a stretched wire to measure the 3 HU256.

Two types of electromagnetic undulators for UV and VUV spectral range have been designed by SOLEIL. HU640 with 14 periods and a peak magnetic field of 0.1 T, is composed of three sets of coils, without iron yokes. This 10 m long undulator has been produced by DANFISIK. Sorting of the coils was performed with the genetic algorithm developed at SOLEIL. Magnetic measurements were carefully carried out at SOLEIL and the undulator was installed on the ring in March 2006.

HU256 is a 3.6 m long elliptical undulator, with 12 periods for a vertical gap of 16 mm, which assembly consists of alternate dipole magnets producing horizontal and vertical components of the magnetic field, with a phase shift of a quarter of period. Three HU256 undulators have been produced by BINP and firstly characterized. The power supplies have been built by DANFYSIK. An extensive campaign of magnetic measurements was carried out at SOLEIL, especially to take into account the hysteresis effect of the device. The first HU256 was installed on the ring in April 06.

SOLEIL has to build 12 undulators for adjustable polarisation in the soft-X ray range. They are based on APPLE II type structures. For the first 3 HU80, a collaboration was established with ELETTRA, who built and measured the two first ones, whereas the third one was build in house. Magnetic measurements were carried out on the first 2 at ELETTRA and on all 3 devices at SOLEIL. The carriages were constructed by RMP (Italy). Motorisation and control of the mechanical movements have been developed at SOLEIL, using Bergher Lahr motors and specific linear encoders, with a mechanical repeatability of a few µm. Genetic algorithm was used for sorting the magnets, for shimming and for magic finger optimisation to reduce phase errors, field integrals and higher order components for the third system whereas simulated annealing was employed for the 2 built at ELETTRA. The first HU80 was installed on the ring in March 2006. Further developments of APPLE-II type undulators go along with a reduction of the period length down to 34 mm.

With the 2.75 GeV SOLEIL energy, undulators with short period and large peak magnetic field are required for the production of radiation in the hard X ray domain. 7 hybrid type 2m long in-vacuum undulators are planned at SOLEIL with periods from 20 to 26 mm. They will be installed in the short straight sections permitting small gap (nominal value being 5.5 mm). The first in vacuum undulator was built by DANFYSIK and was installed on the ring in February 2006. It exhibits a residual phase error of 2.8°. The next in-vacuum ID's are being built by SOLEIL. For the second U20, individual modules of Sm2Co17 magnets alone or together with Vanadium permendur pole have been characterized. The undulator was then assembled using a sorting based on the newly developed genetic algorithm, leading to a max phase error of 2.6° after only few shimming steps.

NEXT STEPS

The commissioning will resume in July. Detailed studies of the beam characteristics and machine tuning will be carried out until the end of 2006. Meanwhile, the commissioning of the first beamlines will start, in parallel with the Ring commissioning from July 2006, with the goal of opening the first beamlines to the external Users early 2007. In the near future, it is planned to implement topping-up injection, to put in operation the transverse bunch by bunch feedback system, as well as a fast global position feedback, and to set up the few bunch mode of operation for time-resolved experiments. Also a low momentum compaction mode will be studied for shortening the electron bunch duration.

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