STATUS OF THE SOLEIL PROJECT

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Abstract

SOLEIL, the 2.75 GeV new French Synchrotron Radiation Facility, located near Paris, is under commissioning. Here are reported the main results obtained especially on the storage ring. The beam dynamics characterisation of the 3.7 nm.rad optics is presented, as well as the first measurements of the instability thresholds. Furthermore comparison is made with expectations of the linear optics model and instability calculations. First experience with innovative devices and technologies is also presented: TANGO control system, BPM system, extensive use of NEG coated vacuum vessels, unconventional RF system (Solid state amplifiers and superconducting cavities). Seven insertion devices accommodating a wide energy range from 5 eV to 30 keV (in-vacuum, Apple II, large period electromagnetic types) are now installed on the machine and some of them are producing the first photon beams which are delivered to the beamlines. Finally a roadmap towards beam delivery to users will be presented.

INTRODUCTION

SOLEIL is designed as a 2.75 GeV third generation light source with 21 out of 24 straight sections (SS) dedicated for installing insertion devices (IDs). This very large ratio of straight sections (43% of the 354 m long circumference, with 29% for magnetic structures) is shared between 4x12 m long SS, suitable for accommodating long period IDs, 12x7 m medium SS, and 8x3.8 m short SS to accommodate in-vacuum undulators. With a small emittance and a target 500 mA beam intensity, the average brilliance will range from 10^{16} to 10^{20} ph/s/0.1%bw/mm^2/mrad^2 for respectively bending magnet and ID based beamlines. Table 1 sums up the main storage ring parameters.

A total of 24 beamlines have been approved by the SOLEIL council. The spectral range is equally shared above and below the energy of 1.3 keV, with a distribution of 6 beamlines on bending magnets (BM) and 18 on ID beamlines, plus 2 IR beamlines.

Here are reported the commissioning results from the Linac to the beamlines with a focus on the storage ring (SR) and the performances reached by the end of 2006.

INJECTOR COMMISSIONING

The injector is composed of two parts, a 100 MeV Linac and a full energy Booster, that were both commissioned in 2005.

The Linac HELIOS is a turn-key system provided by THALES whereas the transfer line from Linac to Booster was constructed by SOLEIL. The performances are better than specifications and have been reported extensively before [1]. In the long pulse mode, the Linac produces a 300 ns train of pulses with a total charge up to 9.3 nC with an energy spread below ± 0.5 % and normalized (4 $\gamma\varepsilon_{rms}$) emittances of 47 (± 10) and 52 (± 10) π mm.mrad respectively in horizontal and vertical planes. For temporal structure a short pulse mode provides 1 to 4 pulses of 1.3 ns with an energy spread of ± 0.6 % for 1 pulse and ± 0.8 % for 4 pulses.

The 3 Hz 157 m long Booster ring provides a 140-150 nm.rad beam emittance at 2.75 GeV. The tracking of the SLS-type digitally control power supplies (dipole and quadrupoles) of ± 0.2 % keeps the tunes within ± 0.05 giving an injection efficiency of 90-95% without further losses during the energy ramping up for different filling patterns. Beam extraction and guiding from Booster to SR transfer line occurred smoothly on May 8th 2006. Further details are given in references [2,3].

Parameter	Value
Energy (GeV)	2.75
Circumference (m)	354.097
Revolution period (μs)	1.18
Betatron tunes H/V	18.2/ 10.3
Energy spread	1.016 10^{-3}
H-Emittance (nm.rad), 1% coupling	3.7
Bunch length @ 4 MV (ps)	14
Damping times H/V/L (ms)	6.56/6.56/3.27
RF frequency (MHz)	352.2

Table 1: Storage ring main design parameters.

STORAGE RING COMMISSIONING

Challenges

Before injecting the first electrons, the storage ring was incorporating new technologies and challenges which potentially, could have jeopardized the commissioning schedule. Final 10 mm vertical aperture 5 m long ID vacuum chambers were installed from day one on the 10 medium straight sections. Moreover the ring was equipped with NEG coated aluminium chambers over 56 % of the circumference, with a SOLEIL designed super conducting cryomodule containing 2 HOM free SC RF cavities, new BPM digital electronics, and 4 insertion devices (1 Apple II type, 1 in-vacuum and 2 electromagnetic undulators). A new type of RF power sources based on solid state amplifiers was implemented to feed the RF cavities. Finally human resources from the support groups (computing, vacuum, alignment…) had to be shared with beamlines to get the first eleven beamlines receiving beam between 2006 and 2007.

Main Milestones

The first electron beam was injected into the storage ring on May 14th 2006 [4,5]. The progress was then very fast as 300 mA (maximum achievable beam current with the present RF configuration) were stored in ¾ filling pattern end of September, after only 8 effective weeks of commissioning. By the end of December 2006, a total current dose of 75 A.h was accumulated (see Fig. 1), and five beamlines had received the photon beam.

During this period, intensive commissioning of the main equipments was performed. Several shutdown periods were dedicated for installing new IDs, for installing and baking out front ends, for cleaning the cooling water circuit polluted accidentally with resin balls (6 weeks), and for replacing badly mounted RF fingers of bellows in some short straight sections.

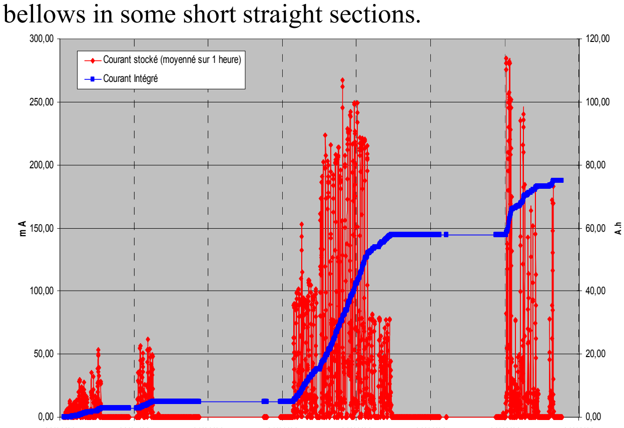

Figure 1: Beam current (red) and evolution of the integrated current (blue) during year 2006.

Closed Orbit

Thanks to very good magnetic measurements (quadrupoles: Δx, Δz = 8.4, 7.5 µm rms , Δθ = 40 µrad rms) [6] followed by a very accurate equipment alignment (60 µm rms for horizontal and vertical quadrupole+girder assembly), the uncorrected rms beam orbit was 3.1 mm and 0.41 mm respectively in horizontal (H) and vertical (V) planes. After calibration of the offsets of the 120 BPMs by beam based alignment [7] and orbit correction, using the standard SVD method applied to the 56 H & V correctors, these values were reduced down to 68 and 58 µm rms. The rms corrector strengths are 0.9 (H) and 0.4 (V) A, *i.e.* below 10 % of their maximum capability.

Beam Position Stability

As reported in [4], to achieve beam stability at a level of 1/10th of the beam sizes, a careful girder design was done with a first resonance mode predicted at 40 Hz: it was determined to be 47 Hz through experimental modal analysing and confirmed by the beam noise spectrum (see Fig. 2). In a spectral frequency span of 0-100 Hz, the integrated beam noise is below 2 µm rms in both planes. Slow thermal drift of a few tens of micrometers will disappear as soon as the tunnel air conditioning is fully operational. Slow and fast orbit feedbacks will be implemented in 2007.

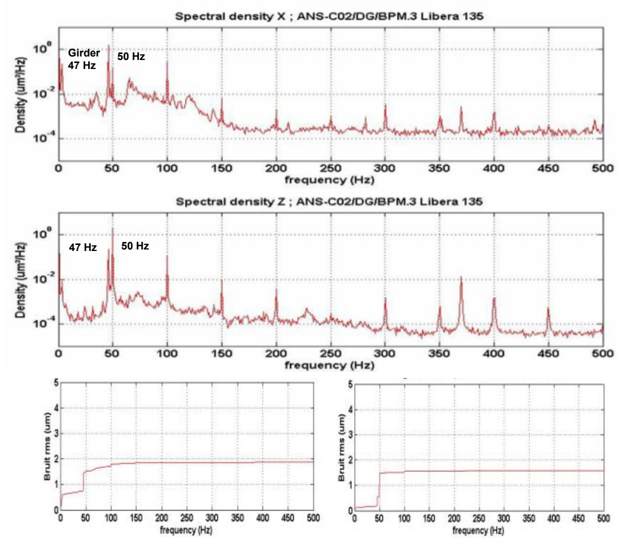

Figure 2: First measured beam noise spectrum using BPM turn by turn data showing an integrated noise less than 2 µm rms in both planes.

Linear Optics

The four-fold symmetry of the lattice has been restored by using the LOCO code [8]. The beta-beats were reduced from 6 (H) and 8 % (V) rms down to 0.8 (H) and 1.0 % (V). The amplitude of variations of the 160 individual quadrupole gradients are still to be understood, especially for defocusing quadrupoles with variation up to 3-4 %.

Natural total chromaticities (-52 and -19) are closed to the model (-53, -23). The main difference in the V-plane is coming from the energy dependence of the dipole fringe field not taken into account in our numerical model.

Betatron coupling deduced from the closest tune approach is about 0.08 % using Guignard formalism [9]. Beam emittance measurement was performed using a pinhole system on a 3.8° exit dipole port. The horizontal emittance was measured at 3.9 ± 0.25 nm.rad (for a design value of 3.7 nm.rad) and the vertical emittance at 11 pm.rad, giving a very low 0.08 % natural coupling (no skew quadrupoles powered on).

Tune shift variations with energy are also very close to the model (see Fig. 3). Minimum acceptance apertures are 5 mm (V-plane) and -15 mm (H-plane) in agreement with the size of the smallest vertical chamber and the horizontal position of the injection Eddy current septum.

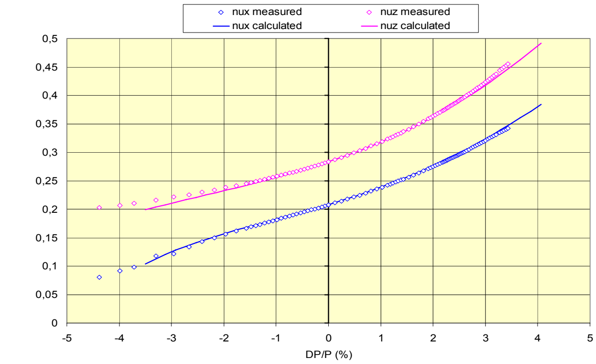

Figure 3: Comparison between measurement and modelling for tune shift with energy for nominal lattice.

High Current and Instabilities

No instability was observed in the longitudinal plane as expected with the superconducting RF cavities.

In multi-bunch mode, a mixture of resistive-wall and ion induced instabilities is observed in both H- and V-planes. The behaviour of the ions induced instability depends much on the beam filling pattern.

The vertical threshold at low chromaticity is in very good agreement with prediction (30 mA), but for larger chromaticity, it is not possible to conclude yet because of the ions. In the horizontal plane, the current threshold seems smaller than the one expected around 90 mA (see Fig. 4 and [10,11]), but the beam is still ion dominated.

Stable conditions up to 300 mA could be achieved with both a ¾ filling pattern and reasonable normalized chromaticities (ξ_H = 0.2, ξ_V = 0.4). For single bunch mode, current thresholds seem to be lower by a factor 2 with respect with the simulations. Further verification is underway.

To combat the transverse instabilities a digital bunch by bunch transverse feedback was installed. The SPring 8 bunch by bunch processor is used, enabling a single loop to correct both planes. For excitation, a dedicated stripline is under construction. First tests with a provisional stripline have shown that the beam can be kept stable up to the maximum current (300 mA) at zero chromaticity in both planes.

Diagnostics

SOLEIL developed BPM electronics in cooperation with Instrumentation Technologies [11]. The resulting electronic rack, called LIBERA, is in the final commissioning phase. The resolution of the BPM electronics for orbit feedback is below 0.2 µm rms within a 100 Hz bandwidth. It also provides turn-by-turn data for machine studies with 3 µm rms resolution (for a 4 mA beam) or 10 Hz data for slow orbit feedback with a 10 kHz data flow for simultaneous fast orbit feedback. Each LIBERA can deliver a position interlock signal. An additional LIBERA is accurately monitoring the tune.

A visible synchrotron monitor and an X-ray pinhole camera are operational for beam imaging enabling to follow beam motions, induced instabilities, and giving beam size measurements.

The first bunch length measurements with a Hamamatsu streak camera gave 45 ps FWHM with 2 MV RF accelerating voltage, a value close to the expected one at low current. The bunch length increases by a factor of two with a current up to 10 mA/bunch.

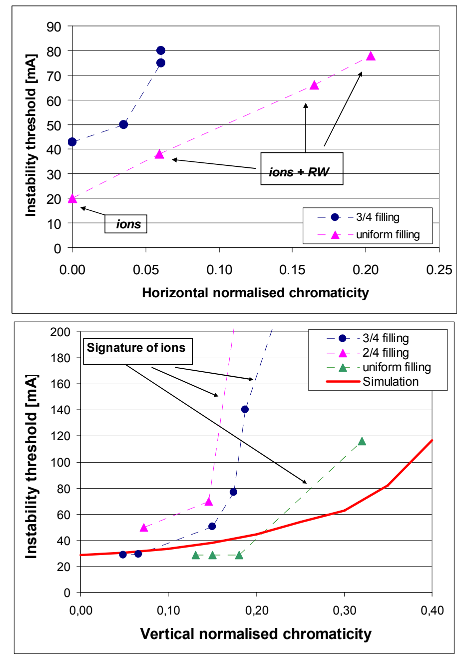

Figure 4: Observed transverse multibunch instabilities thresholds versus normalized chromaticity.

RF System

With the first cryomodule [13,14] the maximum current of 280 mA was reached in operation with no particular difficulties. Before installing the RF-feedback, the cavities were slightly detuned in order to push away the Robinson instability. Overall the RF system is very stable. Further RF conditioning of the cavity coupler will be necessary for continuous operation at 300 mA. No longitudinal instabilities (HOM) were observed on the beam. The two 180 kW solid state amplifiers are running very smoothly. A few transistors failures (18/1450) were observed over 1500 hours of operation but without interrupting the beam. The residual phase oscillation is about 0.1°. The cryogenics plant which maintains the cryomodule at 4 K (50 l/h liquefaction, 400 W refrigeration) is under very reliable operation.

Vacuum System

Average pressure before the first beam was 4 10^{-10} mbar after having baked out the whole ring except the injection section. All vacuum chambers but the dipole ones are in aluminium and coated with a NEG (Non Evaporable Getter) layer with thickness varying from 0.5 (centre) to 1.5 µm (vacuum chamber sides) over a total of 56 % of the ring circumference.

During the commissioning the maximum sustainable current was not limited by the pressure rise due to the photon stimulated desorption but mainly by obstacles in the vacuum vessel reducing the vertical beam stay clear from 5 mm down to 1.5 mm. These obstacles were found to be the consequence of a systematic bad mounting of the RF shield of the bellow of the short straight sections.

In addition, reduction of water flow (presence of resin balls in the cooling water circuit) and bad brazing in the dipole absorber led to abnormal temperature rises. Figure 5 illustrates the average pressure normalized to beam current versus beam dose giving the vacuum conditioning. Radiation measurement downstream the 10 m long NEG coated chamber (14 mm of vertical aperture) showed that Bremsstrahlung rate is negligible at 250 mA.

Twelve front-ends (FE) are now installed inside the SR tunnel. Already 9 FEs are connected to the vacuum vessels in the optics hutches through the shield wall.

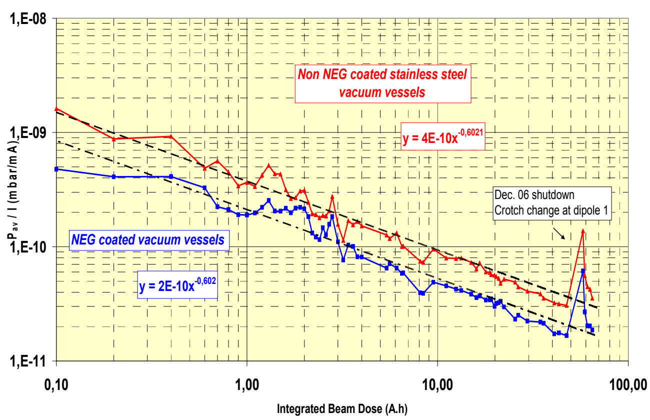

Figure 5: Average pressure of Cell 07 normalized to beam current versus beam integrated dose.

Machine Safety System

The machine protection is fully operational and based on PLCs interconnecting vacuum system and diagnostics.

Using the low latency LIBERA port, the position interlock has been commissioned based on the vertical position reading of all the BPMs upstream the 32 dipoles. Any vertical position larger than ± 1mm trips the beam in less than 10 ms if the stored current is above 20 mA.

For avoiding heating up the narrow part of the vacuum chamber, an instability interlock has been commissioned with success. It consists on a 4.4 mm vertical slit located on a beamport, and locked on the beam through thermocouples. If any large vertical instability occurs the beam is tripped off.

Insertion Devices

By the end of December 2006, seven insertion devices were already installed into the storage ring: 2 Apple II type (HU80), 2 hybrid in-vacuum undulators (U20, 5.5 mm minimum gap), 3 electromagnetic undulators (1xHU640, 2xHU256) [15]. These IDs are under heavy commissioning: beam effect characterization, feedforward table generation, and active compensation on the e-beam.

As the ID control will be partial or total by the beamlines, the full compensation of their effects on the beam (orbit distortion, focusing, emittance coupling) will be quite challenging.

First results are rather promising. For instance, for HU80 and HU256, the residual orbit motion is already around 1.5 µm rms in both planes with feedforward switched on (see Fig. 6). Both U20 were closed at minimum gap without beam losses and with focusing and orbit distortions as expected from magnetic measurements. Because of coil motions of the 10 m long HU640 during dis- and re-assembling of the upper and lower parts, coil repositioning was necessary to reduce large orbit distortions.

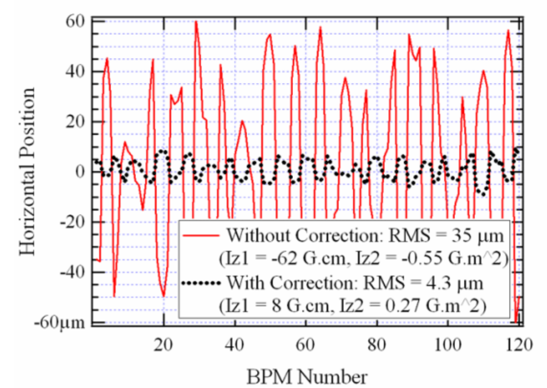

Figure 6: Horizontal orbit distortion without (red) and with (black) feedforward for HU80 tuned in linear horizontal polarization mode.

Control System

For the first time, the TANGO control system is used to control and supervise a full facility from the accelerators to the beamlines. Beam commissioning has been greatly accelerated by using the generic JAVA TANGO applications, and the GlobalSCREEN supervision panels written by operators. Accelerator commissioning has benefited from the Matlab Middle Layer applications fully integrated in the control system. More than 30 000 parameters are supervised from the control room. Use of electronic logbooks, archiving system, and monitoring tools makes all these tasks more manageable (see [16-17] for more details and references within). Main work now focuses on converting expert to daily control applications.

Day to Day Operation

A typical beam lifetime is 10 h for 100 mA stored in ¾ filling pattern with 0.3 % coupling and 2 MV as a total voltage of the RF cavities. Beam lifetime in multibunch mode is still dominated by vacuum pressure.

A total of 1 400 hours of beam was achieved from July to December 2006. Beam availability was close to 83.5 % with 11.2 % of failures (mainly water and power supplies), and 5.3 % including start-up, injection and equipment testing.

Operation group is now complete with 8 fulltime operators. For a 24h/24h and 7 day a week operation, part time operators coming from Machine, technical and computing division (around 70 people) will work up to 12 8 hour shifts per year.

BEAMLINE COMMISSIONING

Between 2006 and 2007, 11 beamlines (BL) will be opened. Energy spectrum extends from IR, VUV to Soft, and Hard X-Rays.

From September to December 2006, 5 BL opened their front-ends (3 on bending magnets, 2 on insertion devices). Thanks to a very good alignment, synchrotron beam was observed almost instantly on a beam screen. On bending magnet beamlines, qualification of the optics and calibration of the monochromator have started and first absorption spectra could be observed. For ID beamlines, the alignment of the first diaphragms and elements has been checked thanks to a so-called DIAGON diagnostics (CCD in case of HU256, multilayer mirror + CCD on HU80). Figure 7 shows the radiation ring pattern using HU80 undulator in case of the vertical linear polarization.

These beamlines are now either under intense commissioning or finishing installing the optics and equipments down to the optical and experimental hutches.

First beam on in-vacuum and IR beamlines are planned for beginning of February 2007. By April 2007, beam time will be allocated to the first users by the peer review committees.

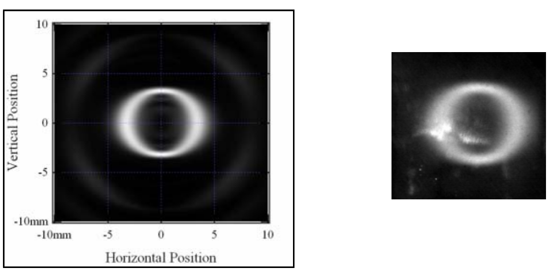

Figure 7: Comparison between SRW simulation (left) and measurement (right) of synchrotron radiation emitted from an elliptical undulator (HU80) at an 180 eV energy.

NEXT STEPS IN 2007

To improve beam stability, the slow, fast orbit feedbacks, XBPMs, and the multibunch transverse feedback will be set into operation.

Characterisation of instabilities, high current operation and studies of 1 and 8 bunch modes will continue.

A digital RF feedback is under development, the second cryomodule enabling to reach up to 500 mA is foreseen by fall 2007.

In parallel, another set of 7 IDs will be installed into the tunnel, and preparation for top-up operation will start.

Opening of the first 11 beamlines to expert or external users will occur in spring of 2007.

AKNOWLEDGEMENTS

Those rapid progresses and successes are mainly due to a strong and very productive interaction and support between the commissioning team and many groups such as the operation, magnetism and insertion, power supplies, RF, Linac, diagnostics, vacuum, alignment, mechanical and engineering, electronics and computer, infrastructure, and safety groups.

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