OPERATION AND PERFORMANCE UPGRADE OF THE SOLEIL STORAGE RING

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Abstract

SOLEIL the French synchrotron light source is now routinely delivering photons to 21 beamlines with a current of 400 mA in top-up mode. The beam position stability is within the one micron range thanks to an original combination of the slow and fast orbit feedback systems, as well as the improved tunnel temperature regulation. The bunch by bunch transverse feedback is running with two independent horizontal and vertical loops. For canted undulator implementations, a three-magnet chicane has been installed in a medium straight whereas an additional triplet of quadrupoles was inserted in the middle of a long straight in order to create a double low vertical beta. 18 insertion devices are presently installed in the storage ring, four will be added in 2010 while another five, including a cryogenic undulator, are under construction,. Following the significant progression of the vacuum conditioning, the lifetime is now mainly Touschek limited. An electron bunch slicing setup is also being installed in order to provide 100 fs long X-ray pulses to two existing beamlines. ~4500 hours of beam have been delivered in 2009 to the beamlines with an availability above 96 % thanks, among others, to the very reliable operation of the unique SOLEIL RF system.

INTRODUCTION

As of May 2010, up to 21 beamlines have taken beam, 13 from Insertion Devices (IDs), 2 from IR ports, and 6 from dipole ports. In 2009, 1719 research scientists have performed 348 experiments on the first 14 beamlines open to external users via peer review committees. In addition, new challenging beamlines are either under construction, using in-vacuum canted undulators or under design like a ~150 m long nano-probe beamline also using canted undulators on a long straight section equipped with an additional quadrupole triplet [1]. The slicing project which aims at providing 100 fs long pulses to several beamlines (soft and hard X-rays) has been launched recently [2]. Nevertheless, the main objective is to continue the optimisation of the accelerator system in order to reach the ultimate performances in brilliance, beam lifetime and beam stability.

STORAGE RING PERFORMANCE

Beam Current in Multibunch Mode

The maximum current during User operation is 400 mA in top-up mode since November 2009. The ring is almost uniformly filled with 4 trains of 100 bunches (out of 416 buckets). The Transverse FeedBack system (TFB) damps the transverse instabilities and maintains the emittance coupling around 1% [3]. In March 2009, it has been possible to store 450 mA in the ring and from that date, all radiation controls were realized at 450 mA on the new beamline hutches. Several attempts were performed to reach 500 mA but this proved to be quite difficult, the main steps are summarized hereafter. Initially, few minutes after a current of 500 mA (or even 475 mA) was stored in the ring, sudden and total beam losses were experienced. As at the same time sudden pressures rises were observed in some locations in the ring, such as inside in-vacuum undulators, it was believed that these losses were due to the so-called fast ion instability. By increasing the vertical chromaticity from 2 to 3.5, it was possible to suppress the beam loss, but the vertical beam size was still blown up to very large values, up to 1 nm.rad (i.e. 30% coupling). Playing with the TFB parameters or the chromaticity proved to be inefficient and we could even stop completely the TFB: the ion effects which were blowing the beam size were strong enough to keep the beam stable with respect to resistive wall and other sources of instability! [4]. Eventually, we found that reducing the RF voltage significantly (from 4 to 3 MV) enabled to push the threshold of these ions instabilities above 500 mA, and since then we can easily store 500 mA at nominal beam sizes (1% coupling). After the radiation survey of last April, the machine can operate at 500 mA without any constraint. During this radiation survey, the 6 in-vacuum undulators installed on the ring were closed to their minimum gaps (5.5 mm) without any problems, which shows that the TFB damps efficiently the resistive wall instabilities.

The 352 MHz solid state RF amplifiers deliver without any difficulty the required 135 kW RF power to each of the 4 superconducting RF cavities. The matching of the RF coupler was by design optimized for 4.4 MV at 500 mA. At 500 mA and 4 MV total RF voltage, the reflected power reaches a few kW on each cavity. At 500 mA and 3 MV total voltage, the reflected power is below 10 kW on each cavity, which is quite acceptable for the solid state amplifiers.

The conditioning of the vacuum vessels has further progressed during the testing periods at 500 mA. Higher pressures developed at some locations of the machine : it was due to temperature increases developing in a few flange connections where the RF contacts, which shield the 0.4 mm gap due to the copper seal, were not acting properly. They were replaced and it solved the issue. The average pressure is now 1 10^{-9} mbar at 500 mA which is within specifications. It demonstrates the efficiency of the NEG coated Aluminium vessels which are extensively used around the ring.

The machine is now ready to operate at 500 mA. Before delivering 500 mA to the beamlines, it will be necessary to perform new radiation surveys around the hutches of all beamlines so as to qualify them for 500 mA operation.

Temporal Structure Modes

Thanks to the installation of optimized striplines, one for the horizontal plane and one for the vertical plane, and with the associated improvements brought to the TFB, it is now possible to also increase the current stored in the so-called "few bunch mode" [3].

For providing a temporal structure at the request of few beamlines, the machine was operated:

- One week in 2009 in hybrid mode, where ¾ of the machine (300 bunches) were filled with a total current of 292 mA and a single bunch of 8 mA was stored in the middle of the empty quart. The beam lifetime of the multibunch train was about 14 h (with 1% coupling) while it was about 4 h for the single bunch.
- One week in 2009 in 8 bunch mode, with a total current of 60 mA, and a beam lifetime of ~4 h at 1% coupling.
- One week in Feb. 2010 in single bunch mode with 10 mA, a beam lifetime of 2.5 h at 1% coupling.

It is foreseen to operate in June 2010 one week in hybrid mode at 400 mA (392 mA in 300 bunches + 8 mA single bunch) and also one week in 8 bunch mode with a total current of 80 mA.

During these time structure modes, the bunch purity, i.e. the ratio between neighbouring bunches to the main one is below 10^{-4}, coming naturally from the short pulse generated by the Linac.

Top-up performance

Top-up mode of operation started in March 2009, at 300 mA. Since November 2009, the machine is routinely operated in top-up mode with 400 mA in multibunch mode. The filling pattern is almost uniform, consisting of 4 batches of 100 bunches, which are topped up one at a time, thanks to the good flat shape of the 300ns Linac pulse.

Because the electron beam lifetime, and the injection efficiency varies strongly according to the IDs configuration, it was not possible to opt for an injection cycle at fixed time intervals. An injection cycle starts every time the current goes below 400 mA, and perform one Linac pulse acceleration and injection. The statistics up to now showed that the complement current shots are between 2 to 3 mA which corresponds to a relative variation of the total beam current of 0.5 to 0.7%. No constraint are set on the IDs which can be set at any gap (or any coil excitation) or any phase, and particularly the in-vacuum undulators, the magnetic gap of which can be set at their minimal value of 5.5 mm. Some of these IDs have significant effects on the lifetime and injection efficiency (see Figure 1) and the interval between two injections varies from 1 to 5 minutes.

A top-up control program is continually monitoring the parameters of the injection chain, i.e., the Linac, TL1, Booster and TL2 equipment, the storage ring injection pulsed magnets, PSS and interlocks. The top-up is inhibited if the values are out of range, or if the injection efficiency is below a pre-determined value. The Booster power supplies are synchronised and are ramped up and down from low currents to nominal currents within 10 second cycles. A few Linac modulator pulses are triggered before the Linac gun is triggered, so, as to guarantee getting a stabilized RF pulse.

Many efforts were made to minimize the perturbations induced on the stored beam by the pulsed elements (septum magnets and kicker bump) and presently the rms residual oscillations of the beam reach 70µm in the horizontal plane and 40µm in the vertical plane. These oscillations are rapidly damped by the TFB, within few ms. Further improvements are expected, though harder to achieve.

The feedback from the beamlines is very positive, even from the infra-red beamlines! The signal/noise ratio read on the detectors is significantly improved and the stability of the optical elements and of the photon beams is highly appreciated. Top-up mode of injection was also implemented in hybrid mode of filling, in 8 bunch mode and in single bunch mode.

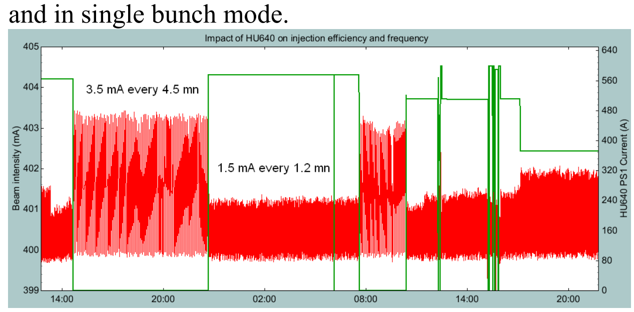

Figure 1: Influence of the HU640 undulator on the injection efficiency and frequency.

Beam Lifetime

The average pressure at 400 mA is now around 9 10^{-10} mbar, the RF voltage optimised for the best lifetime with an acceptable lever of reflected power is about 3.0 MV. Without IDs, in the multibunch mode where 400 (out of 416) buckets are filled, the coupling is close to 0.7%, and the measured beam lifetime at 400 mA is 15 hours. This value can be significantly reduced (down to a few hours) when the 10 m long HU640 undulator is in the Linear Vertical mode at maximum field, and/or when at least 3 of the in-vacuum undulators are at 5.5 mm gap. Experimental investigations have been performed, using Frequency Map Analysis and tune scans, [5], which have confirmed that these devices reduce significantly the energy acceptance of the machine, hence affecting strongly the Touschek lifetime. It was also observed that the beam lifetime is very sensitive to the betatron tunes values for some IDs configurations. In some situations, a variation of the tunes by 10^{-3} can result in a 50% lifetime reduction. A software feedback which, using two quadrupole families, keeps constant the tunes, was implemented and significantly minimizes the amplitudes and number of drops in the beam lifetime.

Mastering of beam losses

With the increasing operation stored current (400 mA and soon 500 mA), the losses induced by a beam dump can generate high radiation doses outside the tunnel. In order to guarantee that the dose rates outside the tunnel never exceed the limit acceptable for public access, a large number of gamma-ray and neutron monitors are distributed on the storage ring tunnel roof and along the external walls. They operate in integration mode and whenever the dose integrated over 4 hours exceeds 2 μSv, they prevent injecting a new beam by interlocking the Linac gun. During the shutdown of January 2010, a new vacuum chamber has been installed in a short straight section in order to enable the coming installation of an 11mm gap Apple-II type undulator [6]. The horizontal inner width of this new chamber is smaller than the usual ones, and reduces the physical aperture from +35/-35mm to +27/-30mm. Due to the large non linear dispersion in such short straight section (similar to the one in the middle of an achromat) when the RF system is stopped (due to a machine interlock during user operation for example), the entire beam is lost at this location, generating a high dose on the tunnel roof gamma-ray monitor, which then interlocks beam injection during up to 4 hours. In order to avoid falling in that scenario, the horizontal chromaticity has been increased from 2 to 3.6 so that, due to the strong variation of the horizontal tune with energy, the beam is lost by explosion on the integer resonance before it reaches the vacuum chamber. The beam losses are then distributed along the ring and as each radiation monitor sees only a fraction of the loss, they stay well below the interlock threshold. However, this increased horizontal chromaticity has some impact on the lifetime as shown on Table1, and this should be considered as a temporary solution.

Table 1: Beam lifetime measured with a 400 mA stored current in multibunch mode for the bare machine

Chromaticities H/V	RF voltage=4 MV	RF voltage= 3 MV
0/0		15 h
2.0/2.6	15 h	
3.0/2.6	15 h	
3.6/2.6	12 h	12.5 h

It is foreseen to implement a horizontal scraper in the achromat close to the injection section, so as to collect these losses at a place where the shielding is larger.

Beam Position Stability

Two orbit feedback systems are used to stabilize the beam position at all source points. The Slow Orbit FeedBack (SOFB) running at 0.1 Hz runs a closed orbit correction scheme using 120 BPMs and 56 dipolar correctors in each plane. The latter are located in the sextupoles. The Fast Orbit FeedBack (FOFB) running at 10 kHz is using the same 120 BPMs and 48 dedicated air coil correctors installed around the upstream and downstream bellows of each of the 24 straight sections. Thanks to a sophisticated communication protocol, both feedback systems operate together. This original and innovative scheme provides a very efficient correction over the 0-to-200 Hz frequency range without any dead band [7]. The short and long term stabilities at all the source points are about one micron in both planes.

OPERATION

During 2009 the total operation time was 6 028 hours spread over 7 runs. The machine dedicated time was 22%. Up to 4 423 beam hours were effectively delivered to the beamlines and associated radiation controls, resulting in an availability of 96.4% of the scheduled beam time. The MTBF reached 34.5 hours over the year. With the top-up operation, the longest uninterrupted beam delivery period was 132 hours. Over the period from June 2009 till April 2010, the availability was further improved reaching 97.3% over 3858 hours of beam time, and with 18 weeks (over 27) above 98% availability. Over the same period, the MTBF increased to 45 hours.

INSERTION DEVICES

There are now 18 IDs installed on the ring: 4 electromagnetic helical and 9 APPLE II undulators with periods ranging from 80 to 44 mm, and 5 in-vacuum undulators (4xU20+1xU24). Four other IDs, will be installed by this summer: 1 U20, 1 APPLE II with a very short 36 mm period [6], an in-vacuum wiggler (to cover the 20-50 keV photon energy range [8]) and an electromagnetic/permanent magnet helical undulator for fast polarization switching. Another five are under construction including a prototype cryogenic in-vacuum undulator [9].

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