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First operation of SOLEIL, a third generation synchrotron radiation source in France and prospects for ARC-EN-CIEL, a LINAC based fourth generation source

M.E. Couprie[a,*], J.M. Filhol[a], C. Benabderhammane[a], P. Berteaud[a], J.C. Besson[a], F. Briquez[a], P. Brunelle[a], C. Bruni[a], O. Chubar[a], J.C. Denard[a], M. Girault[a], J.M. Godefroy[a], C. Herbaux[a], P. Lebasque[a], V. Le Roux[a], M.P. Level[a], A. Lestrade[a], A. Loulergue[a], P. Marchand[a], O. Marcouille[a], F. Marteau[a], M. Massal[a], A. Nadji[a], L. Nadolski[a], R. Nagaoka[a], F. Paulin[a], B. Pottin[a], M.A. Tordeux[a], M. Valleau[a], J. Vétéran[a], B. Carré[b], D. Garzella[b], M. Labat[b], G. Lambert[b], P. Monot[b], M. Jablonka[c], F. Méot[c], A. Mosnier[c], J.R. Marquès[d], J.M. Ortéga[e]

[a]*Synchrotron SOLEIL, Saint Abin, BP 34, 91 192 Gif-sur-Yvette, France*
[b]*CEA/DRECAM Service de Photons, Atomes et Molécules, France*
[c]*CEA/DAPNIA Service des Accélérateurs, de la Cryogénie et du Magnétisme, France*
[d]*Laboratoire d'Utilisation des Lasers Intenses, École Polytechnique, France*
[e]*Laboratoire de Chimie Physique, Université de Paris-Sud, France*

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Abstract

The first results of commissioning for the French Synchrotron Radiation Facility SOLEIL at 2.75 GeV are presented. Perspectives for the fourth generation light source based on the ARC-EN-CIEL project are described.

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Keywords: Storage ring; Synchrotron radiation; Free electron laser

1. Introduction

France has a long tradition on synchrotron radiation, in the UV–soft X-ray on ACO (1973–1989), Super-ACO (1987–2003) and hard X-ray second generation light source such as DCI (1975–2003) rings at Orsay, and on the third generation hard X-ray source European Synchrotron Radiation Light Source (ESRF) (from 1992) at Grenoble. The new facility SOLEIL, aiming at providing synchrotron radiation for the French user community to complement ESRF and replace Super-ACO and DCI, consists of an injector (100 MeV LINAC and 3 Hz full energy booster synchrotron) and a 2.75 GeV storage ring of 357 m circumference. Designed as a low emittance (3.7 nm rad) synchrotron radiation source with a modified Chassman Green optics, it accommodates a total of 162 m of straight sections (4×12 m, 12×7 m, 8×3.6 m) [1], for up to 21 insertion devices (ID). High average brilliance radiation extends from the IR–UV–VUV up to the hard X-ray domain (20 keV), ranging from 10^{16} (respectively, 10^{18}–10^{20}) ph/s/0.1% BW/mm^2/mrad^2 for the bending magnets sources (respectively, ID). Electrons first circulated in a few turns (May 14th, 2006), were then stored and accumulated in early June 2006. Nowadays, a current of 300 mA has been stored. First beamlines have been opened: DIFFABS (bending magnet beamline for absorption,

*Corresponding author. Tel.: +331 69 35 98 02; fax: +331 69359451.
E-mail address: marie-emmanuelle.couprie@synchrotron-soleil.fr (M.E. Couprie).

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Table 1
SOLEIL characteristics

Nominal energy (GeV)	2.75
Circumference (m)	254.097
Revolution period (μs)	1.18
Number of cells/super-periods	16/4
Betatron tunes ν_x; ν_z	18.2; 10.3
Momentum compaction (α_1, α_2)	$4.38 \times 10^{-4}/4.49 \times 10^{-3}$
Relative energy spread	1.016×10^{-3}
Damping time (longitudinal, transverse) (ms)	3.27/6.56
Emittance (nm rad)	3.74
Total radiation power loss for 500 mA (kW)	575
Bunch length (ps)	13.8
Linac pulse/train duration (ns)	300/1.13 (MR) 1.3 (TS)
Linac total charge (nC)	9.3 (MR), 0.52/p (TS)
Linac energy spread (%)	$\pm$0.5 (MR) $\pm$0.58 (TS)
Linac emittance (π mm mrad) horizontal/vertical	47 ($\pm$10)/52 ($\pm$10) (MR) 64$\pm$10/67$\pm$10 (TS)

MR: mulitbunch regime; TS: temporal structure (single pulse mode).

September 13), TEMPO (first undulator beamline, September 21st), ODE (bending magnet beamline for dispersive EXAFS, October). SOLEIL characteristics are given in Table 1.

After a long tradition in free-electron laser (FEL), both on storage ring based FELs (ACO, Super-ACO) and on infra-red LINAC based FELs (CLIO, ELSA), the fourth generation light source activity in France is based on the ARC-EN-CIEL proposal. After considering the installation of an FEL in the VUV on SOLEIL in the oscillator or coherent harmonic generation configurations, it was decided to propose an independent LINAC based dedicated facility providing coherent radiation down to 1 nm, for easier access of the users. ARC-EN-CIEL [2] aims at developing a strong synergy between the FEL and the laser communities. The innovative choice of seeding the FEL with high order harmonic produced in gas, at a high repetition rate leads to a significant shortening of the wavelength of the seed, in addition to the advantages of seeding with respect to SASE (pulse to pulse intensity stability, reduction of jitter, compactness, enhanced longitudinal coherence). Indeed, more than 70% of the users intend to perform pump-probe experiments and a high stability is requested, as discussed in the frame of the user workshop “Applications of VUV X fs tuneable sources combining accelerators and laser: “slicing” at SOLEIL and the ARC-EN-CIEL project” (February 3–4, 2004, Orsay). Besides, propositions of plasma acceleration and Thomson scattering emerged from the laser–electron beam combination. A high repetition rate (1–10 kHz) from a superconducting LINAC as forseen by the users, permits also efficient injection of the high harmonics produced in gas, and high electron beam stability. The possible implementation of the first phases in the former tunnel of the Accélérateur Linéaire de Saclay, next to SOLEIL, would make a very attractive accelerator based light source complex.

2. The third generation light source SOLEIL

2.1. The injector

The SOLEIL 100 MeV 352 MHz LINAC (THALES) produced its first beam on July 2nd. After various adjustments, the first turns and rapidly up to 2 million runs were performed in the booster, with magnets arranged in a FODO lattice, on July 23rd. The beam has been stored with an injection occurring at 3 Hz (every 340 ms) (October 8th, 2005), ramped in energy ramping at 2.75 GeV (October 13th, 2005) and extracted from the booster (May 8th, 2006).

2.2. The ring

The dipoles (TESLA), quadrupoles (DANFYSIK), and sectupoles (SIGMAPHI) were characterized in terms of magnetic axis and field properties. The quadrupole measurements led to mean (respectively RMS) position of 1.5 (respectively 8.4) μm in horizontal H, 2.6 (7.5) μm in vertical V, and 8 (40) μrad in tilt. The 124 sextupoles led to mean (respectively average) position of −3 (15) μm in H, 2 (10) μm in V and l0 (1 0 0) μrad in tilt. Main power supplies are from Hazemeyer, correctors' ones from Bruker.

The vacuum system comports the 2.5 m long dipole vacuum chambers (SDMS), aluminium with NEG coating chambers (SDMS, SAES) for all straight sections and quadrupoles. Ten 10 mm inner aperture ID vacuum vessels have been installed in the medium straight section from the beginning.

The superconducting technology RF cavities aiming at a good longitudinal stability consists of two cryomodules with two cavities leading to a maximum power of 600 kW. The first cryomodule (ACCEL) provides 150 kW/coupler and 1.5 MV/cavity at 352 MHz for 300 mA operation, while 500 mA are expected in 2007 with the second cryomodule. Each cavity is powered by a 190 kW solid state amplifier developed at SOLEIL consisting in a combination of four 50 kW “towers”, combining the RF power amplified by all the 320 W elementary modules.

Various 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, beam loss monitors, and a streak camera. In all 120 temperature stabilized beam position monitors (BPM) are distributed along the ring and with the LIBERA electronic modules (I-Tec) for the control of the electron orbits with a submicron resolution. Turn by turn reading of the BPM was used efficiently during initial commissioning.

Pulsed magnetic equipments (septum magnets, kickers) are designed in house. Special care was devoted to the magnetic shield of the eddy current septum magnet for top-up injection: the stray field seen by the stored beam is reduced to 10 ppm of the main field.

The SOLEIL control system is based on TANGO, with hardware components such as Programmable Logic

(SIEMENS), Compact PCI crates, and standalone motion controllers. It is connected with the higher level via a dedicated switched Ethernet, and supervised with GlobalScreen (ORDINAL) application providing also Data Acquisition. Matlab Middle Layer tool kit was used for the commissioning.

2.3. The electron beam commissioning

The installation of the components of the storage ring, including the first four ID, was completed in May 2006. On May 14th, 2006, the beam could be circulated for the first time up to 9 turns without any corrections, with beam settings close to the theoretical values (see Fig. 1). Its trajectory was followed using the turn by turn BPMs and synchrotron radiation could be observed on a CCD camera. The first beam (0.3 mA) was stored on June 2nd, followed by its accumulation (8 mA) on June 4th. Presently in Fall 2006, 300 mA has been reached. The lifetime is 8 h at 100 mA. With the setting deduced from the beam-based alignment, the RMS value of the closed orbit is reduced to 62 μm in horizontal and 58 μm in vertical. The high level of longitudinal stability has been confirmed by streak camera measurements.

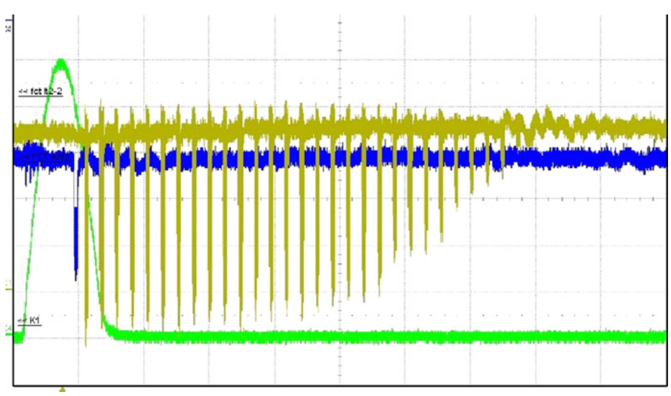

Fig. 1. Different turns detected by the FCT located 14 cells downstream the injection point, 5 μs/div.

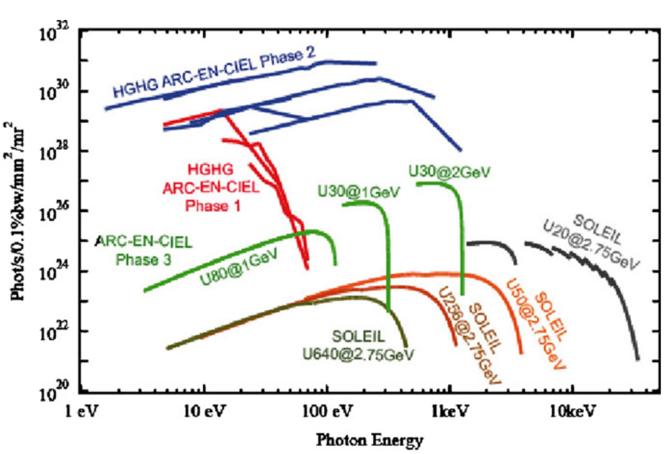

Fig. 2. Peak brilliance. Phase 1: HGHG radiation + seeding wavelength, $P_{seed} = 100$ kW for HHG harmonics nos. 7–9, 600 kW for nos. 3–5. 1 kA, $F = 0.1$. Phase 2: HGHG radiation 1.5 kA, 1.35π mm mrad, 0.0004% slice energy spread, 200 fs, beta = 2 m, $F = 0.088$. Phase 3: spontaneous emission of undulators of period 30 and 80 mm calculated with SRW. Undulator period length in mm in ID name.

Future developments include topping-up injection, a transverse bunch by bunch feedback system, a fast global position feedback, a few bunch modes of operation for time-resolved experiments and the study of a low momentum compaction mode for shortening the electron bunch duration.

2.4. Light sources for users from undulators and IDs

In short straight sections, the beam sizes (divergences) are 388 μm (14.5 μrad) in horizontal and 8 μm (4.6 μrad) in vertical. In medium straight sections, the beam sizes (divergences) are 182 μm (30.5 μrad) in H and 8 μm (4.6 μrad) in V. In long straight sections, the beam sizes (divergences) are 281 μm (19 μrad) in H and 17.3 μm (2.2 μrad) in V. For 4° bending magnet beamlines, the beam sizes (divergences) are 43 μm (107 μrad) in H and 24.5 μm (2.1 μrad) in V.

Front-ends comport Gamma steppers, acoustic delay lines, fixed absorbers, and shutters. The design is rather compact. The installation of 12 front-ends is almost complete.

The energy range covered by the SOLEIL ID extends from the UV to hard X-ray (see Fig. 2), starting from HU640 and 256 mm period electromagnetic adjustable polarisation undulators to APPLE-II type undulators and in vaccum undulators and wiggler [3].

3. The ARC-EN-CIEL project

ARC-EN-CIEL is planned into three phases: a first phase reaching an energy of 220 MeV for high gain harmonic generation (HGHG) sources in the VUV, a phase 2 at 1 GeV with HGHG sources down to 1 nm using high harmonics produced in gas, and a phase 3 including two recirculation loops, for energy recovery or energy enhancement with undulators (12 m long, period 30 and 20 mm) for providing subpicosecond radiation in the VUV and X-ray ranges (5×10^{12} phot/s/0.1% bw for 0.1 mA average current). In addition, a 0.1–1 kW average power, 0.1–1% bandwidth FEL oscillator, installed in the first loop, could cover the 120–10 nm, thanks to recent development of multilayer mirrors for lithography, and normal incidence SiC mirrors. Harmonics can also be produced from the FEL oscillator, with 500 MW at 4.5 nm and 10 MW at 2.7 nm. The beam at 2 GeV from the loop will allow shortening further the radiation wavelength down. Expected radiation from ARC-EN-CIEL is illustrated in Fig. 2, comparing radiation of its three phases with respect to the ID of SOLEIL. THz radiation will also be provided.

3.1. The accelerator part

The gun should provide 1 nC for 1π mm mrad total emittance. The first solution relies on a RF photo-injector equipped with a CsTe cathode, modified to operate at 1 kHz (coupler). A longer-term system is based on a superconducting gun, where emittance compensation and reliability can still be an issue. The adaptation of the CeB6 thermo-ionic gun developed at RIKEN for the SCCS project is also under consideration [4]. In the first phase, the RF gun, is followed by a first TESLA type cryomodule, bringing the energy to 100 MeV, a third harmonic cavity compensating the non-linearity of the longitudinal phase space, a S-chicane compressor, and a second cryomodule raising the energy to 220 MeV. Additional 6 modules are included in phase 2. Along the bunch compressor, the total emittance is raised to 2.7π mm mrad in the chicane (from 2.1 to 0.1 mm/300 fs rms). With a proper electron beam optics, the slice emittance along the bunch remains almost unchanged (ranging from 0.7 to 1.1) with a small mismatch from slice to slice.

3.2. The laser system

The laser system is based on a passive mode locked Ti:Sa based oscillator, (1 W, 76 MHz, 13 nJ/pulse), feeding three branches: a first one, devoted to the photo-injector, with ~50–100 μJ pulse energy in the UV (266 nm) at 1 kHz, with DAZZLER-based shaping and frequency tripling, a second one, a broadband system based on 10 mJ multi-kHz chirped pulse amplification delivering system for seeding, and a third branch for high power at a few Hz.

3.3. The light sources

ARC-EN-CIEL phase 1 plans to use a 26 mm period in-vacuum hybrid undulator as a modulator, and a 30 mm Apple-II undulator as a radiator. Identical sections of modulator and radiator will be added for the second phase of ARC-EN-CIEL (4–8 m for the modulator, and 4 sections of 4 m for the radiator). Such undulators are currently developed for SOLEIL third generation facility.

Collaborations have been set up for demonstrating the feasibility to seed a LINAC-based FEL with HHG on SCSS phase 1 in Japan [5] and on SPARC in Italy [6]. FEL radiation based on analogous systems for ARC-EN-CIEL is calculated using PERSEO 1D code [7] with a gain reduction due to the filling factor and a new test version of SRW allowing the wavefront to be transported in the beamline to the user sample.

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