**Facility Reports**

*J. Synchrotron Rad.* (1998). **5**, 1157–1161

# Commissioning and Operation of the First Brazilian Synchrotron Light Source

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(*Received 4 August 1997; accepted 28 November 1997*)

The synchrotron light source designed and constructed at the LNLS is composed of a 1.37 GeV electron storage ring and a 120 MeV linac for low-energy injection. The storage ring has been commissioned and has already reached the designed electron-beam energy, current and emittance. The electron lifetime is now 6 h at 60 mA, and is steadily increasing. Seven beamlines (TGM, SGM, SXS, XAFS, XRD, SAXS, PCr) have been constructed in parallel with the electron accelerators and are at present in operation. Beam time was allocated to 129 approved research projects for the second semester of 1997. A number of them are currently under way.

**Keywords: synchrotron light source; beamlines; commissioning.**

## 1. The LNLS synchrotron light source

The National Synchrotron Light Laboratory (LNLS/CNPq) was established in 1987 by the Brazilian National Council for Scientific and Technological Development (CNPq) with the objective of constructing a synchrotron light source and the associated beamlines to be utilized for a wide range of scientific and technological applications.

The synchrotron source, at present in operation and open to users since 1 July 1997, is composed of a 1.37 GeV electron storage ring and a linear accelerator which injects into the ring at 120 MeV. The energy of the electrons is ramped up to the final energy inside the storage ring. Originally, the storage ring was designed for 1.15 GeV/100 mA with some allowance in the power supplies and vacuum chambers to deal with higher synchrotron light power. However, the care taken in the design and construction of the magnets proved sufficient to increase the energy to 1.37 GeV, which means twice as much synchrotron light power and 30 times more flux at 10 keV.

**Figure 1**
The LNLS 1.37 GeV electron storage ring. Inside the ring, two klystrons and their associated modulators may be seen; they feed the linac located underground with RF.

Most of the components of the synchrotron source were constructed at the LNLS, including all magnets and power supplies. Detailed descriptions of these components have been published elsewhere: magnets (Neuenschwander *et al.*, 1997), power supplies (Wisnivesky *et al.*, 1997), RF system (Wisnivesky & Pardini, 1997), vacuum components (Ferreira *et al.*, 1997), interlock system (Scorzato & Rodrigues, 1997), control system (Tavares *et al.*, 1997).

Fig. 1 shows a general view of the LNLS electron storage ring. The linac injector is located underground.

Three modes of operation of the electron storage ring have been studied. They are the high-, normal- and low-emittance modes. The main design parameters of the LNLS synchrotron source for the normal mode of operation are listed in Table 1.

The commissioning of the LNLS synchrotron light source started in May 1996. The full electron energy of the storage ring (1.37 GeV) was attained, with a few mA, in October 1996. The electron current at full energy has

**Table 1**
Main design parameters of the LNLS electron storage ring.

| | |
|---|---|
| Operation energy | 1.37 GeV |
| Injector | Linear accelerator |
| Injection energy | 120 MeV |
| Nominal electron current | 100 mA |
| Circumference | 93.21 m |
| Mean diameter | 30 m |
| Magnetic structure | Double-bend achromat |
| Lattice symmetry | Six fold |
| Revolution frequency | 3.2 MHz |
| Harmonic number | 148 |
| RF frequency | 476 MHz |
| Natural emittance | 100 nm rad |
| Horizontal betatron tune | 5.27 |
| Vertical betatron tune | 2.17 |
| Synchrotron tune (at 500 kV RF gap voltage) | $9.19 \times 10^{-3}$ |
| Natural horizontal chromaticity | −7.8 |
| Natural vertical chromaticity | −9.5 |
| Momentum compaction factor | $8.3 \times 10^{-3}$ |
| Natural energy spread | $6.0 \times 10^{-4}$ |
| Horizontal betatron damping time | 13 ms |
| Vertical betatron damping time | 13 ms |
| Synchrotron damping time | 6 ms |
| Dipole bending radius | 2.735 m |
| Bending field | 1.67 T |
| Number of dipoles | 12 |
| Number of insertion-device straight sections | 4 |
| Length available for insertion devices | 2.95 m |
| Energy loss per turn from bending magnets | 114 keV |
| Total radiated power from bending magnets | 11.4 kW |
| Critical photon energy from bending magnets | 2.08 keV |
| Electron lifetime | 10 h |

increased steadily, reaching the design value of 100 mA in July 1997. Fig. 2 shows a plot of the electron current as a function of energy during the first ramping procedure in which the design value was attained.

The experimentally measured emittance of the source is 100 nm mrad, in agreement with the design value. The electron-beam lifetime is now 6 h at 60 mA of stored current, and is steadily increasing. The vertical and horizontal positions of the beam are maintained within 20 µm using an automatic periodic correction of the orbit.

In order to increase the electron current above its design value, an upgrading of the electron linac is being considered. Modifications to raise the injection energy up to 170 MeV may be carried out during a shutdown scheduled for November–December 1997 if it proves necessary.

Fig. 3 shows the photon flux produced by the bending-magnet sources of the LNLS electron storage ring. The useful photon energy range (*i.e.* the range for which the photon flux is much higher than that produced by classical sources such as, for example, a rotating-anode source) extends up to $E_{\rm max}$ = 15 keV. In order to increase the photon energy range for users interested in applications of higher-energy photons ($E_{\rm ph}$ > 10 keV), the insertion of superconducting wigglers in the straight sections of the ring is planned. The photon flux expected from a planned 1/2–1–1/2 wiggler (wavelength shifter), with a magnetic field of 7 T, is also plotted in Fig. 3.

## 2. LNLS beamline

The main technical characteristics of the first seven beamlines, now in operation at LNLS, are listed below.

(i) *Toroidal-grating monochromator (TGM)* (Fonseca *et al.*, 1992). Source: bending magnet D05 (4°), $\sigma_y$ = 0.14 mm. Monochromator: three toroidal gratings. Energy range: 300–100 eV (40–120 Å), 100–35 eV (120–360 Å), 35–12 eV (360–1000 Å). Spectral resolution: better than 0.1 Å (40–120 Å), better than 0.3 Å (120–360 Å), better than 1.1 Å (360–1000 Å). Dispersion: better than 30.2 Å deg$^{-1}$. Focusing elements: two toroidal mirrors. Flux on sample: $10^{13}$ photons s$^{-1}$ (1.3 GeV at 100 mA). Spot size at sample: 2 × 5 mm. Detectors: electron energy analyser, fluorescence detector, electron time-of-flight.

(ii) *Spherical-grating monochromator (SGM)* (Castro *et al.*, 1993). Source: bending magnet D08 (4°), $\sigma_y$ = 0.10 mm. Monochromator: two spherical gratings. Focusing elements: two spherical mirrors and one toroidal mirror. Energy range: 250–1000 eV (250–1500 eV at reduced flux and resolution). Spectral resolution: better than 3000. Spot size at sample: 0.5 × 0.5 mm. Detectors: electron energy analyser, channeltrons, microchannel plates.

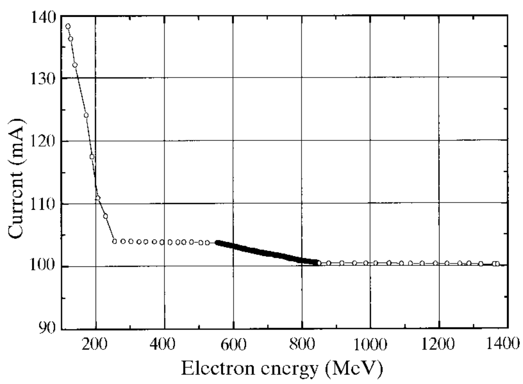


**Figure 2**
Electron current (mA) during an energy-ramping procedure (July 1997).

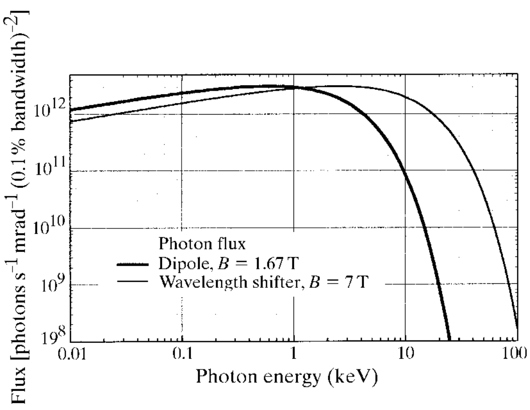


**Figure 3**
Photon flux from the bending magnets of the storage ring and from the planned 7 T wavelength shifter.

(iii) *Soft X-ray spectroscopy (SXS)* (Tolentino, Compagnon-Cailhol *et al.*, 1998). Source: bending magnet D04 (4°), $\sigma_y$ = 0.10 mm. Monochromator: double-crystal with constant offset (Correa *et al.*, 1992). Energy range: beryl, 790–1550 eV; quartz, 1480–1800 eV; InSb, 1680–2000 eV; Si, 2050–4000 eV. Energy resolution: 0.2 eV at 800 eV ($E/\Delta E$ = 4000). Focusing element: toroidal mirror (gold-coated zerodur mirror). Detectors: total electron yield, electron energy analyser, photodiode array.

(iv) *X-ray absorption fine structure (XAFS)* (Tolentino, Cezar *et al.*, 1998). Source: bending magnet D04 (15°), $\sigma_y$ = 0.12 mm. Spot size: 550 × 700 µm. Flux on sample: 2 × $10^9$ photons $s^{-1}$ $mrad^{-1}$ at 8 keV. Monochromator: double-crystal (Correa *et al.*, 1992) and four-crystal (Tolentino & Rodrigues, 1992) with constant offset. Energy range: Si(111) ($2d$ = 6.271 Å), 2.010–11.390 keV; Si(220) ($2d$ = 3.84 Å), 3.300–18.500 keV; Ge(111) ($2d$ = 6.53 Å), 1.920–10.930 keV. Resolving power ($E/\Delta E$): 10000–100000. Focusing system: cylindrical bent mirror (gold or rhodium-coated), sagittal focusing on crystal. Detectors: ion chambers, fluorescence and electron detectors.

(v) *X-ray diffraction (XRD)* (Cusatis *et al.*, 1998). Source: bending magnet D12 (4°), $\sigma_y$ = 0.10 mm. Monochromator: double (2C) (Correa *et al.*, 1992) and four- (4C) (Tolentino & Rodrigues, 1992) crystal with constant offset. Energy range: Si(111) ($2d$ = 6.271 Å), 2.010–11.390 keV; Si(220) ($2d$ = 3.84 Å), 3.300–18.500 keV; Ge(111) ($2d$ = 6.53 Å), 1.920–10.930 keV. Energy resolution: 4 eV at 8000 eV ($E/\Delta E$ = 2000). Focusing element: sagittal focusing (10 mrad) by elastic bending of the second crystal (2C). Detectors: fast scintillation detector, Si–Li solid-state and linear position-sensitive detector, ionization chamber, fluorescence detector, imaging plate.

(vi) *Small-angle X-ray scattering (SAXS)* (Bernardes *et al.*, 1992). Source: bending magnet D11 (4°), $\sigma_y$ = 0.14 mm. Monochromator: one horizontally bent and asymmetrically cut silicon crystal, reflection (111), asymmetry angle 11°, condensing mode. Energy range: 6–12 keV (1–2 Å). Energy resolution ($E/\Delta E$): 1000. Focusing element: cylindrical elastically bent mirror (vertical focusing), bent silicon crystal (horizontal focusing). Detector: one-dimensional position-sensitive gas detector, two-dimensional position-sensitive gas detector, imaging plate, scintillation monitors.

(vii) *Protein crystallography (PCr)* (Polikarpov *et al.*, 1997). Source: bending magnet D3 (15°), $\sigma_y$ = 0.12 mm. Monochromator: single horizontally bent and asymmetrically cut silicon crystal, reflection (111), asymmetry angle 7.25°, condensing mode. Energy range: 6–12 keV (1–2 Å). Energy resolution ($E/\Delta E$): 3000. Focusing elements: cylindrical elastically bent mirror (vertical focusing), bent silicon crystal monochromator (horizontal focusing). Detector: imaging plate.

Two additional beamlines for X-ray fluorescence (XRF) studies and microfabrication (MF) are currently under construction and will be open to users in 1998.

The locations around the storage ring of the beamlines mentioned above are indicated in Fig. 4. All beamlines were designed and constructed at LNLS. Some of the optical components developed at LNLS, such as two-crystal and four-crystal monochromators, use original and patented mechanical concepts (Cusatis, 1993; Tolentino & Rodrigues, 1993). A picture of one of the X-ray beamlines (SAXS) in operation is shown in Fig. 5.

## 3. Preliminary experimental results and status of LNLS beamlines

Preliminary experiments using LNLS beamlines had been performed by the end of October 1996. As an example of

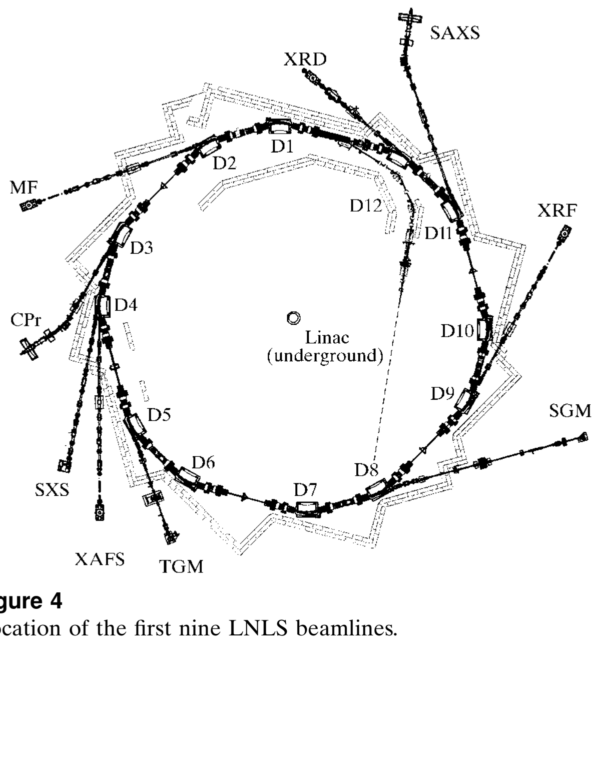


**Figure 4**
Location of the first nine LNLS beamlines.

**Figure 5**
The SAXS beamline. The beamline passes across the shielding on the left. The sequence of optical components is: mirror chamber (for vertical focusing), first four-slit set, monochromator chamber (for monochromatization and horizontal focusing), second four-slit set, guard slit set, sample holder, beamstopper and vertical X-ray position-sensitive detector.

the first experimental results, an EXAFS spectrum of pure nickel is shown in Fig. 6. This absorption spectrum was obtained in the XAFS beamline using two ion chambers to record the direct and transmitted beam intensities as a function of the photon energy. The white beam was monochromatized by using the (111) Bragg reflection from a two-crystal silicon monochromator. The absorption coefficient of Ni was determined in an energy range of 500 eV, close to the $K$-absorption edge. Atomic structure information is obtained by mathematical treatment of the EXAFS oscillations which are apparent in Fig. 6 above the $K$-absorption edge.

Other recent experimental results concerning (i) XAFS studies of the atomic structure of nanocrystalline Cu–Co alloys and (ii) SAXS investigations on the crystallization process in polymers and on conformational changes of lysozyme in aqueous solutions, were reported in the XX Brazilian Meeting on Condensed Matter Physics (June 1997).

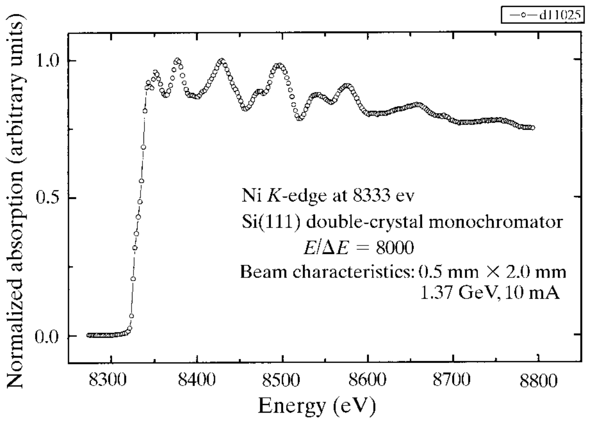


**Figure 6**
EXAFS spectrum of Ni close to the $K$ edge (Tolentino, 1996).

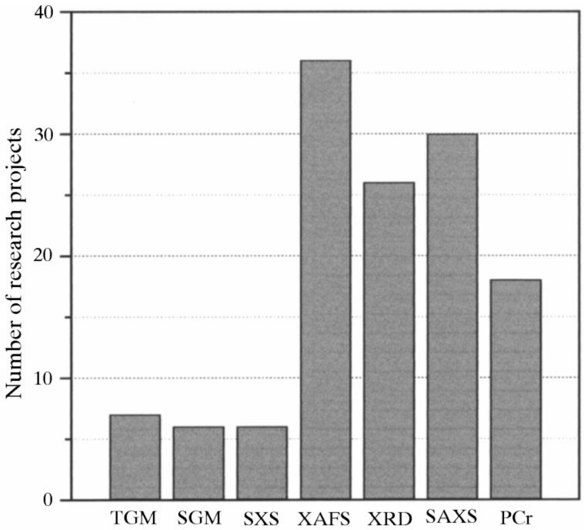


**Figure 7**
Distribution of the approved projects among the different beamlines.

The LNLS source has been operating for about 100 h per week since 1 July 1997, with 55 h dedicated to synchrotron light users. Up to now (27 August 1997), 129 research projects have been approved by the Scientific Committee (16 from foreign countries) for the second semester of 1997. A number of them are currently under way. The distribution of approved projects among the different beamlines in operation, shown in Fig. 7, exhibits a strong concentration for the hard X-ray techniques. Experiments requiring particularly high hard X-ray photon flux will be possible when the planned superconductor wiggler is installed.

## 4. Conclusions

The 1.37 GeV LNLS electron storage ring is presently in operation and has been open to users since 1 July 1997. The main design parameters of the source have been achieved and the total beam time for users, scheduled for the first two months of operation (July–August 1997), was fully delivered.

In parallel to the effort of building the light source, seven beamlines were constructed and commissioned. They are now being used by the scientific staff of LNLS and by many scientists from other Brazilian and foreign research institutions.

The technical achievement related to the successful construction, commissioning and operation of the LNLS synchrotron light source, the first in the southern hemisphere, is an important milestone for Brazilian science and technology. It is expected that the use of the LNLS synchrotron source by materials scientists, biologists and researchers from many other fields will provide a significant contribution to the development effort in Brazil and Latin America.

Additional information about LNLS and on the procedure for submitting research proposals is given on the LNLS Internet home page (http://www.lnls.br/).

The authors thank the LNLS technical, administrative and scientific staff, thanks to whom this project was accomplished.

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