# THE BRAZILIAN SYNCHROTRON LIGHT SOURCE

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### Abstract

The Brazilian Synchrotron Light Laboratory has been operating the only light source in the southern hemisphere since July 1997. During this period, approximately 22000 hours of beam time were delivered to more than 1000 users from all over Brazil as well as from 10 other countries. In this paper, we briefly recall the history of the project and describe the present configuration of the machine and associated instrumentation, focusing on improvements and upgrades of the various light source subsystems and beamlines implemented in recent years. Finally, we report on the use of the facility by the national and international scientific communities and present perspectives for future improvements of the machine as well as plans for new beamlines.


## A BRIEF HISTORY OF THE PROJECT

### The Early Years: Why a Synchrotron Light Source in Brazil?

Although the first discussions about a Synchrotron Light Source for Brazil took place at the Centro Brasileiro de Pesquisas Físicas (CBPF) in Rio de Janeiro as early as 1981, it was only in 1985 that the decision was taken to fund a design effort and a small team of physicists and engineers was sent for a short period to the Stanford Synchrotron Radiation Laboratory (SSRL) and, in collaboration with Prof. Helmut Wiedemann, prepared the first draft of a conceptual design report for a 2 GeV light source. That design report (later known as Project 1) was the basis for cost estimates and further discussions within the Brazilian government and scientific community, which finally led to the creation, in 1986, of the Laboratório Nacional de Luz Síncrotron (LNLS), a research institute funded by CNPq, the National Research Council of the Ministry of Science and Technology.

The choice of a synchrotron light source as the first modern National Laboratory in Brazil arose from a perception of the need to develop accelerator technologies, basic experimental research and applied materials research as well as a new model of scientific organization in the country. The rationale behind the idea of this project was based on a three-fold strategy [1]:

(a) a large challenging engineering project that could attract a critical mass of young scientists and engineers to be trained in key technologies thus speeding up the development of these fields in the country.

(b) the construction of an experimental facility that could provide state-of-the-art resources to a wide spectrum of researchers, including physicists, chemists, biologists, crystallographers, materials scientists as well as medical and industrial users, and finally

(c) the introduction of the concept of a national laboratory, providing open access facilities to be used mainly by researchers from other institutions, with only a reduced in-house scientific staff producing high quality scientific results and keeping the facility up-to-date.

Basically all of these assumptions remain true to this date, although the spectrum of applications that were envisioned in 1986 was somewhat changed as a result of recent advances in various areas of synchrotron radiation instrumentation and data analysis. This is particularly true in regard to the enormous increase of interest for synchrotron radiation from the biology research community, in connection with protein crystallography techniques.

### Building the Synchrotron

Following the strategy outlined above and in order to provide training to a group of enthusiastic but inexperienced accelerator builders, the first task given to the fledgling accelerator staff was the design and construction of a linear accelerator, later to become the injector for the storage ring. The injector LINAC uses standard travelling wave disk-loaded constant gradient waveguide structures operating at 2856 MHz. Although the final design of the injector was made for a 120 MeV machine, floor space constraints limited the injector energy at this time to 50 MeV. The 50 MeV LINAC was designed and built in about 2 ½ years and the beam was detected at the end of the second accelerator structure in December 1989 [2].

After completion of the first half of the linear accelerator, the efforts of the construction team turned to the review of the design of the storage ring. The need for a thorough revision of the first conceptual design (Project 1) arose from two different reasons : first, Project 1 was written in 1985 when the research with insertion devices was still in its infancy and therefore it proposed a FODO arrangement for the storage ring magnets, which had insufficient free space for the future installation of wigglers and undulators; second, financial constraints were now clearer to the board of directors of LNLS, who decided that a different specification for the light source had to be put forward in order to allow for a timely completion of the whole project. As a result of that decision, a series of design studies was started that culminated in the UVX-2 project: a 1.15 GeV VUV and soft X-Ray light source, whose parameters were defined according to the following criteria [3]:

- Critical photon wavelength below 10 Å so as to make the light source interesting for applications in materials science and in atomic and molecular physics, areas in which there was an immediate need in Brazil.


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- Lattice with long straight sections to accommodate insertion devices,
- Beam lifetime of the order of 10 hours
- Conservative magnet design.
- Reliable operation.
- Low energy injector.
- Small number of magnetic elements.

Following these guidelines, the LNLS staff designed and built all machine subsystems, including magnets, power supplies, vacuum system, control system, interlocks and diagnostics.

The full 120 MeV injector LINAC was assembled in its tunnel and successfully operated on December 22$^{nd}$, 1995. Early in 1996, the LINAC-to-Storage Ring transport line was completed and by March 1996 all of the magnets were in place, connected to the power supplies and the vacuum chambers installed and pumped down to the ntorr range. The first stored beam was observed on May 30th but the accumulation process was still very difficult and the stored current saturated at about 0.3 mA. The efforts at this time split into two main tasks: accumulation at 120 MeV and energy ramping. While energy ramping evolved quickly with a systematic approach, accumulation turned out to be much more challenging and could only be mastered through many adjustments and a thorough scan of betatron tune space. In fact, the first stored beam at the nominal 1.15 GeV was observed in July 1996 but only in October did the commissioning team succeeded in accumulating 20 mA at injection energy. Finally, in May 1997, the stored current had reached 120 mA at 1.37 GeV and the machine was delivered for routine operation for synchrotron light users in July 1997 with seven beamlines in operation.

## IMPROVING THE LIGHT SOURCE: UPGRADES TO THE INJECTOR AND STORAGE RING

Even though the successful commissioning of the LNLS storage ring made available to the Brazilian scientific community an extremely valuable instrument, the light source delivered in 1997 suffered from various limitations, mostly related to the funding difficulties during the design and construction phases of the lab.

Our main problems were related to the low energy injection system (a 120 MeV LINAC), which imposed the need for the storage ring to perform the multiple tasks of storing beam at low energy, ramping it up to the nominal energy – about a factor 10 higher then the energy at injection - and then maintaining the beam stored with a good lifetime while delivering photons to users. The large dynamic range of the energy ramp had various deleterious impacts on the properties of the beam at injection energy, such as perturbations caused by remnant fields of the storage ring magnets and the small radiation damping rates and large intra-beam scattering growth rates, which resulted in a fairly large stored beam size. All this resulted in low reproducibility of the injection process, low injection efficiency as well as the need for a fairly large aperture for the injected beam, particularly in the vertical plane, making the installation of small gap chambers for insertion devices difficult.

On top of that, the storage ring vacuum and RF systems were originally designed for an energy (nominally 1.15 GeV) lower than the energy made possible by the maximum field actually reached by the dipole magnets (1.37 GeV), so that thermal and RF power considerations limited the amount of current that could be stored at this higher energy. Also, even though four 3-m long straight sections had been kept free for the installation of insertion devices, no such magnets were available at that time.

Finally, orbit measurements were slow and noisy and depended on multiplexed RF front-ends. Large (few hundred microns) orbit drifts could be observed and associated with thermal effects, but no on-line correction system was available.

Over the past few years, basically all of those limitations have been dealt with, the main improvement being the addition of a booster synchrotron to the injection system. Table 1 shows the main machine parameters and Figure 1 shows a layout of the storage ring and injection system. The electrons are produced in an 80 keV electrostatic gun with a gridded dispenser cathode and accelerated to 120 MeV in four accelerating structures located in a tunnel below the level of the storage ring. A booster synchrotron accepts the electrons at 120 MeV and accelerates them to 500 MeV before ejecting the beam into the storage ring. The whole procedure is repeated every 6 seconds and it takes typically 4 -5 minutes to fill up the storage ring with 250 mA. Once the beam is stored, the beam energy is ramped to the nominal 1.37 GeV in about 40 seconds and delivered to users. Typically the lifetime at 200 mA is about 15 hours and grows to 25 hours at 100 mA.

### *The Magnet Lattice*

The storage ring uses a six-fold symmetric Chasman-Green achromat and has 12 rectangular bending magnets which produce a maximum field of 1.67 T, providing a 2 keV critical photon energy. The achromatic arcs connect six 4-meter long dispersion-free straight sections, four of which allow for insertion devices. The double bend achromatic arc uses two quadrupoles to match the dispersion. Apart from the standard operation mode, three additional operation modes, a higher emittance, a lower emittance and a low vertical beta mode have also been designed. The low beta mode proved very useful in the recent commissioning of our first insertion device, allowing the gap of a 2.0 T wiggler to be closed without the need for orbit or tune corrections.

### *Magnets*

All magnets in the accelerators are made from 1.5 mm thick low carbon steel laminations. The conventional method of fabrication for such laminated magnets is to manufacture a cutting tool and then have the laminations punched, which provides for a very fast production line. At LNLS however, it was found that the time required by local industry to produce the cutting tool and the prices involved made it attractive to use a different technique: a laser cutter was acquired from industry and all laminations were cut in the lab to within 0.02 mm tolerances. The use of a laser cutting machine added enormous flexibility to the magnet design procedure allowing many prototypes to be tested and special shapes to be produced.

Table 1: Main LNLS storage ring parameters

| | | |
|---|---|---|
| Nominal Energy | 1.37 | GeV |
| Injection Energy | 500 | MeV |
| Nominal Current | 250 | mA |
| Circumference | 92.2 | m |
| Critical Photon Energy | 2.0 | keV |
| RF frequency | 476 | MHz |
| Betatron Tunes | 5.27/2.17 | Hor/Ver |
| Straight Section Free Length | 3 | m |
| Equilibrium emittance | 100 | nmrad |
| Coupling | 0.3 | % |

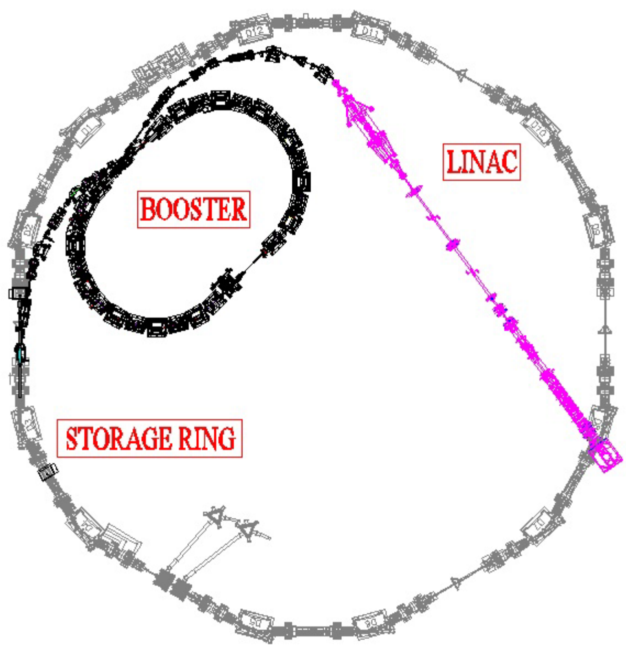


Figure 1: Lay-out of the LNLS Light Source.

## Vacuum System

All vacuum chambers were designed and built at LNLS, whereas pumps and vacuum instrumentation were purchased from industry. The most challenging part of the system is the dipole vacuum chamber since this is where mostof the synchrotron radiation power has to be dissipated and the synchrotron radiation induced desorption rate has to be controlled. The dipole chambers are made of 316L TIG-welded stainless steel and have two synchrotron light ports, NEG strip pumps, one long clearing electrode (CERMET coated alumina) and a water cooled copper absorber.

The whole vacuum system was designed and constructed before the storage ring dipole magnets were shown to reach higher fields than originally foreseen, thus allowing an increase of the nominal electron beam energy. As a result, the original vacuum system specifications were not adequate for the currents that could be stored after the installation of the booster synchrotron. In order to overcome this limitation, the dipole chamber cooling system was upgraded in 2002 with the inclusion of cooled copper masks at the chamber exits in order to protect the stainless steel welds from the high power density deposited by synchrotron radiation at those points. This was part of a larger vacuum upgrade effort which also included the replacement of the original in-vacuum ferrite injection kickers with new ceramic chamber kickers. In fact, after commissioning of the booster synchrotron, overheating of the in-vacuum kickers produced by interaction with beam induced fields could be observed, when large currents in a few bunches were stored at low energy. The ceramic chambers developed by LNLS are 30-cm long oblong tubes brazed to kovar rings at the extremities and coated with titanium in order to provide electrical continuity for the electron beam image currents.

The most recent addition to the storage ring vacuum system is a small (19 mm) gap, 3-m long insertion device chamber. This chamber uses the simple concept of pressing a cylindrical stainless steel tube into an elliptical shape and then TIG-welding it to a precision machined support that provides mechanical rigidity. Since there is no ante-chamber and ion pumps are installed only at the ends of the chamber, a NEG film was deposited to provide distributed pumping along the chamber [4].

## RF System

The originally installed RF system included a commercial high power transmitter, a single cell bell-shaped cavity purchased from Sincrotrone Trieste and an in-house developed low level control with amplitude and frequency loops and could deliver up to 60 kW at 476 MHz.

This system was upgraded in 2003 in order to increase the available power so as to allow larger currents to be stored and also provide the necessary additional power in order to compensate for the demands imposed by the installation of insertion devices. Cost and logistic considerations led to the decision to simply duplicate the whole system, with the addition of an identical RF cavity and power plant. Even though the low level system was completely rebuilt, the basic system configuration is the same, with the important addition of a klystron output phase control loop, to keep the phase between the two systems fixed. Commissioning of this new system met with difficulties associated with the excitation of longitudinal higher order modes in the new cavity and attempts to use temperature and plunger tuning to avoid interaction of the beam with these modes were only partly successful. A final solution to stabilize the beam was found in the form of phase modulation of the main RF


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drive signal at a frequency close to twice the synchrotron frequency, which also provided the added benefit of a longer electron beam lifetime [5,6].

### *Control System*

The control system was totally developed in house, including the low level interface boards, the low level local controller software, the serial interfaces and the high level control software. That decision was partly motivated by the difficulties in obtaining industrial standard automation components in Brazil at a time when computer products were only allowed into our country under heavy taxation. Those circumstances led to the development of a cheap custom-made system well adapted to the specific needs of LNLS

A major upgrade program is currently under way for the control network with the aim of integrating industrial standard protocols that will be easier to maintain and expand [7]. One example of that is the addition of an Ethernet node to the control network dedicated to the control of the recently installed multipolar wiggler.

### *The Booster Synchrotron*

Design work on an upgraded injector for the light source was started in July 1998. An increase of the injection energy was considered necessary for two reasons (a) injection efficiency had already reached its maximum at the low injection energy (120 MeV) and further improvements of the storage ring current could only come from an improved injector and (b) the vertical beam dimensions at 120 MeV made it very hard to install small gap insertion devices, a growing demand from the LNLS user community. The option for an intermediate energy machine (500 MeV) was the result of a compromise between injection efficiency, physical space available, minimal disruption to routine user operation and cost. The booster synchrotron was built at LNLS within 2 ½ years and was commissioned [8] in Nov. 2000, after which the beam current in the ring achieved a record of 540 mA at the new injection energy of 500 MeV.

Even though many of the booster subsystems are similar to their storage ring counterparts, some special developments were necessary considering the particular needs imposed by the smaller circumference and shorter magnets in the booster. One example was the development of the booster dipole magnets, for which edge effects had to be taken in account very carefully through detailed field mapping and particle tracking [9]. Also, for the booster RF system, a 1 kW power source was developed in-house by combining power from solid state amplifier modules developed in collaboration with LURE (Figure 2).

### *Orbit Control and Stability*

The first orbit measurement and correction system upgrade program was initiated in 1998, when various improvements were implemented, such as higher resolution for corrector AD boards, the elimination of RF multiplexing from BPM readings, the increase in the number of vertical correctors, and the operation of an orbit correction feedback loop. Recent improvements in orbit control include new BPM AD converter boards, better shielding/external triggering of BPM electronic modules and new BPM data analysis systems [10]. Also, X-Ray BPMs for the dipole beamlines were recently developed and are currently under tests at a diagnostics beamline [11].

Figure 2: Solid State RF amplifier module and power combiners developed for the booster synchrotron.

### *Insertion Devices*

Our first insertion, installed and commissioned [12] in February 2005, is a 30 pole 2.0 T Hybrid multipolar wiggler optimized for the production of 12.4 keV photons to be used primarily as the source of radiation for a protein crystallography beamline. The wiggler was specified by LNLS and built by STI Optronics Inc.

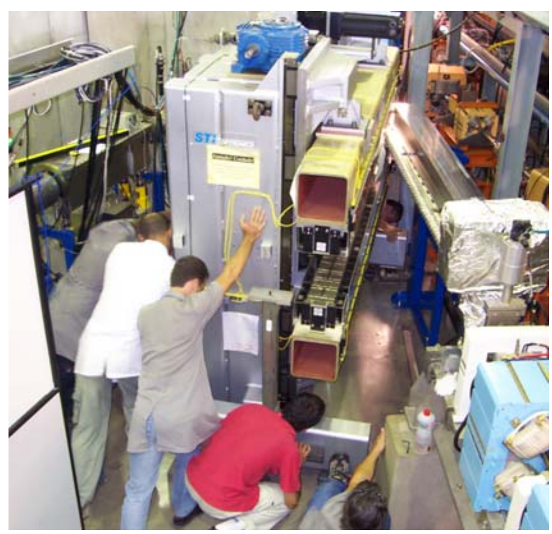

Figure 3: Bringing the 2.0 T wiggler into position.

A second insertion device is currently under construction at LNLS: an elliptical undulator optimized to produce radiation in the UV and soft x-ray range (180 eV to 1 keV) with complete control of polarization. The undulator period is 50 mm and the vertical peak field at minimum gap (22 mm) is 0.52 T.

Design work was recently started on future insertion devices for the LNLS machine. A magnetic design has been proposed that would reach 2.7 T in a hybrid configuration with a 14 mm gap, increasing the flux at 20 keV by a factor 640. This design is an attempt to satisfy user needs for higher flux at high photon energies by taking permanent magnet technology to its extremes and avoiding the high costs involved in superconducting magnets.

Figure 4: Assembling the prototype Elliptical Undulator.

### *Beamlines*

Today a total of 12 beam lines are in operation at LNLS, 9 in the harder X-ray part of the spectrum and 3 in the VUV and soft X-ray. Other five beamlines are either under construction, commissioning or design. Together with our two diagnostics beamlines, these take up 19 out of 24 possible spots around the storage ring.

## MACHINE RELIABILITY AND USE

In nearly 8 years of continuous operation, machine reliability has always been a major concern of LNLS. From the very start, automatic procedures were established to measure machine reliability and log machine fault events, in order to allow for easy identification of frequently faulty subsystems and detect reliability bottlenecks. This effort allowed the overall facility reliability to increase from an initial 92% in 1997 to 98% in 2003.

Beam time allocation is done, as is common in other synchrotron light sources, by beamline committees which analyze scientific proposals for experiments submitted by researchers of Brazilian and foreign institutions, including universities, research institutes and private companies. In 2004, close to 400 research projects were carried out at the LNLS beamlines and this number has been increasing steadily over the years as well as the number of publications resulting from those projects (379 in 2004)

## FUTURE PERSPECTIVES

New developments of the LNLS light source that are currently under way include the forthcoming installation of our first elliptical undulator (and corresponding beamline) and design work on a high field (2.7 T) hybrid wiggler and beamline applications in materials science. Also the possibility of raising the storage ring energy to 1.6 GeV is currently under consideration. This would be done by increasing coil currents in our existing magnets and pushing their field to the limit of 1.95 T. Prototype work is currently under way in order to demonstrate the principle. The implementation of an optical configuration with a reduced emittance (50 nmrad) mode is also planned. Equally important are improvements to orbit stability with the implementation of feedback loops based on X-ray BPMS as well as fast feedback to counteract coherent oscillations.

Finally, at this time internal discussions on concepts for a new machine for LNLS are just starting.

## CONCLUSIONS

LNLS designed, built and operates the first large particle accelerator in the southern hemisphere. Apart from the technical achievements, the successful operation of such a complex device is a very significant event in the history of Brazilian Science and Technology, since this is the first time a large civilian project is carried out completely from design to the operational phase. The interest shown by the scientific community in using the source over the past years demonstrates that LNLS has become an important tool for the advancement of science in our country.

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