LEAPING TOWARDS BRILLIANCE

In its final stage of construction, the latest-generation synchrotron light source could elevate the quality of Brazilian research

TEXT **Ricardo Zorzetto**

PHOTOS **Léo Ramos Chaves**, from Campinas, SP

It was almost six o'clock in the early evening of Thursday, May 17, when electrical engineer Sergio Marques took the opportunity to stretch his legs and look for more energy in yet another cup of coffee. Then, he would resume taking the measurements his team had been working on since the beginning of the week, together with Brazilian physicist Liu Lin's research group, sometimes for 24 hours at a stretch. Marques and Lin, both researchers at the Brazilian Synchrotron Light Laboratory (LNLS) in Campinas, in central São Paulo State, had been testing the components of a linear electron accelerator purchased for US$6 million from the Institute of Applied Physics in Shanghai, China. Installed during the previous weeks in a 32-meter tunnel with concrete walls, every half a second the device propels microscopic packets of trillions of negatively charged particles at close to the speed of light. The accelerator will feed the largest, most complex and versatile research instrument ever built in the country: Sirius, a state-of-the-art source of synchrotron radiation, which is a special type of light that allows researchers to investigate the structure of matter at the scale of atoms and molecules.

Sirius has been under construction since 2014 at the Brazilian Center for Research in Energy and Materials (CNPEM), 15 kilometers from Campinas. It should be ready for an initial test by the end of this year, if the requested funds approved by the federal government months ago are released soon. The new synchrotron light source is a particle accelerator comprising three parts. It is installed in a 68,000 square-foot building that must remain as isolated as possible from temperature changes and external vibrations, especially those generated by truck traffic on the highway connecting Campinas to Mogi-Mirim, which is two kilometers away.

Designed by the LNLS teams, Sirius will replace the UVX, the first source of synchrotron light in the Southern hemisphere. Built in the 1990s, today the UVX is no longer competitive. Approximately 90% of Sirius's components were developed at the LNLS workshops or designed there and produced by Brazilian high-tech companies. The linear accelerator is an exception. "Due to time concerns, we commissioned a machine with

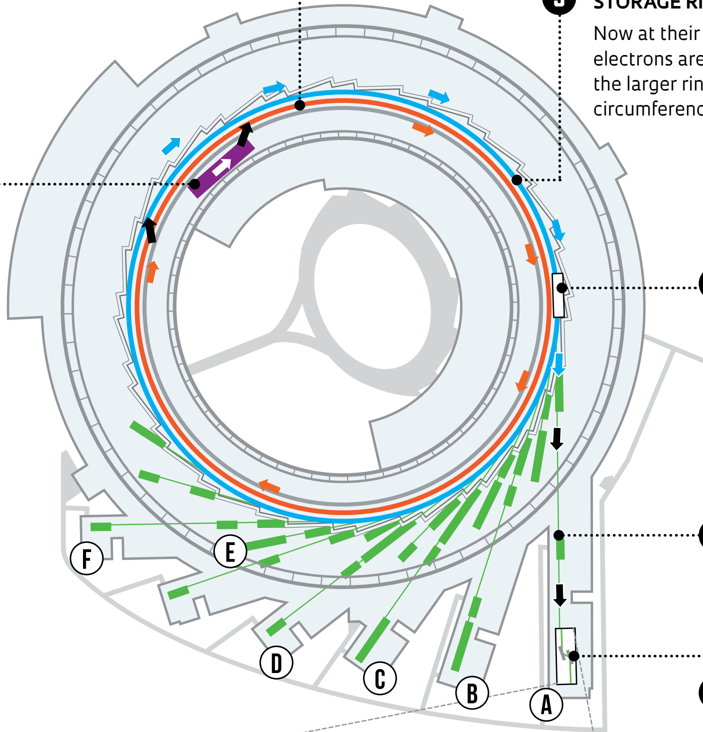
Detail of an wiggler, a series of magnets that make the electrons snake inside the storage ring and release energy in the form of synchrotron light

A special kind of light

When it goes into operation, possibly in 2019, Sirius will be one of the most brilliant sources of synchrotron radiation in the world

SOURCES HARRY WESTFAHL JR / LNLS / CNPEM AND THE SIRIUS PROJECT

FROM ELECTRONS TO RADIATION



1 LINEAR ACCELERATOR

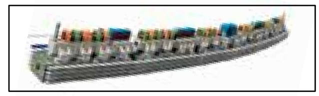
Electrons released by a heated metal filament are propelled in a 32-meter-long linear accelerator to nearly the speed of light, with 0.15 giga-electron volts (GeV) of energy and injected into the *booster*

2 *BOOSTER*

Inside a smaller, inner ring, the electrons gain energy by passing through a radio-frequency chamber and attain 3 GeV of energy

3 STORAGE RING

Now at their maximum energy, the electrons are kept in a stable trajectory in the larger ring, 518 meters in circumference, by sets of special magnets



4 MAGNETIC LATTICE

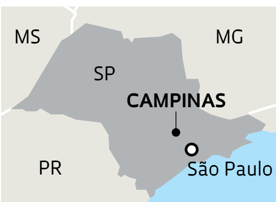
By passing between dipole magnets and undulators, electrons undergo trajectory deviations and lose a fraction of their energy in the form of light: it is this light, or synchrotron radiation, that spans a wide range of energy (from infrared to X-rays)

5 SYNCHROTRON LIGHT

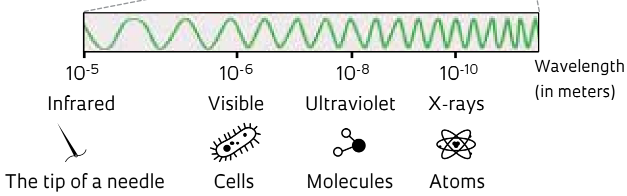
The synchrotron light leaves the ring tangentially and is sent to the experimental stations

6 EXPERIMENTAL STATIONS

Optical setups equivalent to prisms installed at these stations allow selection of the range of radiation that will be used to analyze samples. Each range of radiation is appropriate for observing structures at different scales, ranging from fractions of a millimeter down to the nanometer



Sirius is located approximately 15 kilometers north of the city of Campinas



THE FIRST BEAMLINES

Of the 13 beamlines planned to complete Sirius, all named after Brazilian trees, the six identified below will be the first to go into operation

A CARNAÚBA

This will be the longest beamline, at 145 meters in length. Its beam of X-rays will resolve objects down to 30 nanometers (a resolution 1,000 times higher than that of Brazil's current light source, the UVX). It will enable two- and three-dimensional analysis of catalyst materials, semiconductors, and biologicals with nanometer resolution

B CATERETÊ

An X-ray beamline that will enable the acquisition of three-dimensional images of living cells and can register dynamic phenomena on the order of fractions of a second, such as alterations in molecules of DNA. It will allow researchers to observe the interaction between chemical elements in different materials, as well as the nanoscale structures of oils and polymers

C EMA

Its ultrabright X-ray beam will produce nanometer-scale images of materials under extreme conditions (temperature, pressure, and strong magnetic fields), which are important for the research of superconducting materials. It will feed equipment at two experimental stations

D MANACÁ

This will be the first beamline assembled at Sirius, with completion scheduled for April 2019. Its X-ray beam will be used to analyze protein crystals, enabling scientists to obtain three-dimensional images of their molecules that show the precise location of each atom

E MOGNO

One of Sirius's most energetic X-ray beamlines, Mogno, is expected to generate 3D images of nanometer-scale structures of dense materials in just seconds. It will be capable of penetrating centimeters into rocks taken from oil reservoirs. The current light source can analyze samples with only fractions of millimeters of thickness. Mogno will also enable the study of live animals

F IPÊ

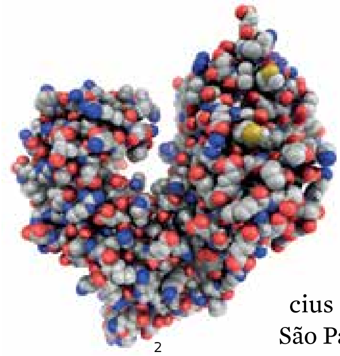
This light source will work with low energy X-rays and will enable the mapping of electrons responsible for the physical properties of matter, such as magnetism and electrical conductivity. It will make it possible to observe the formation of chemical bonds between atoms of matter in solid, liquid, and gaseous states high-level specifications from researchers who had completed a third-generation synchrotron light source in Shanghai, one generation prior to Sirius, and they provided us data on almost every part of the accelerator," Marques explains. He began working at the UVX in 1997 at the age of 16 and now leads the LNLS diagnostic group, which monitors the electron beam and the quality of synchrotron light that arrives at its experimental stations.

When it goes into full operation, Sirius will be—for a limited time—the most advanced source of synchrotron light in the world, in addition to being the brightest X-ray spectral source in its energy class (*see article on page 10*). Put simply, this means that the accelerator will allow researchers to extract very concentrated beams of light from electron streams traveling at almost 300,000 kilometers per second. These beams that can penetrate deep into dense materials such as rock and will produce clear images of objects only a few nanometers (millionths of a millimeter) apart. The intense brightness of the beams will reduce the image acquisition time from samples from hours to seconds, which is crucial in the study of biological materials, which degrade rapidly. The reduction in the time needed to produce each image will allow a greater number of images to be obtained per second and enable scientists to reconstruct the movement of very fast phenomena at the level of atoms and molecules, such as interactions between two compounds, or the movement of ions in charging and discharging batteries.

Sirius's resolving power will outpace third-generation synchrotron light sources such as the current technology at the European Synchrotron Radiation Facility (ESRF) in France. Israeli researcher Ada Yonath performed some of the experiments that defined the three-dimensional structure of the ribosome—the protein-producing organelle in cells—at the ESRF, which earned her the 2009 Nobel Prize in Chemistry. Images from Sirius are also expected to achieve a resolution up to 1,000 times better than that of the UVX, which is a second-generation light source.

1

Aerial image of the Sirius building, taken in mid-June in 2018



2

The three-dimensional structure of the NS5 protein of the Zika virus, defined atom by atom

Even though it is out of date, the UVX allowed physicist and professor Glaucius Oliva and his team at the University of São Paulo (USP) in São Carlos to identify the three-dimensional structure of the NS5 protein, which is essential to Zika virus reproduction (*see* Pesquisa FAPESP *issue no. 254*).

With the new synchrotron in Campinas, researchers expect to go even further and identify the three-dimensional structures of larger, more complex proteins of interest in biology and pharmaceuticals and study materials of interest to industry (*see infographic on following page*). "Sirius is very close to the limit of what engineering can currently build, and will be able to produce internationally competitive science for at least a decade," says physicist Antônio José Roque da Silva, director of the LNLS and the Sirius project. A professor at USP and a specialist in the mathematical modeling of materials at the atomic scale, Silva arrived at the LNLS in 2009 with two missions: first, to improve the UVX, which as an aging technology was beginning to lose users and researchers to institutions abroad, and second, to carry out the project of building its replacement. The name Sirius would come later, borrowed from the brightest star in the night sky.

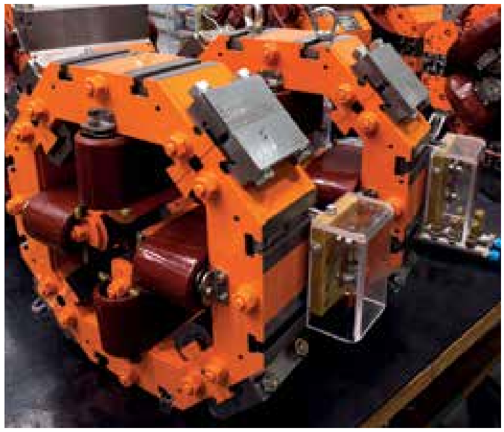
From the beginning, Silva sought the help of two former LNLS collaborators: civil engineer Antonio Ricardo Droher Rodrigues, one of the three Brazilians who led the construction of the UVX from 1987 to 1997, and French physicist Yves Petroff, who directed synchrotron light labs in France and participated in the first Brazilian light source project. "The UVX no longer had the ability to compete, so we opted to improve in niches where we could produce relevant research using infrared and ultraviolet radiation," Silva says. At the same time, the trio perfected a third-generation light source project developed by the team led by physicist José Antônio Brum, who directed the Brazilian Association of Synchrotron Light Technology (ABTLuS), now CNPEM, from 2001 to 2009. Three years later, with a mature project in hand, Silva and his team submitted their project to an international scientific committee.

In their final report, the committee members said the design of the new light source was excellent according to the current standards, but they recommended that the team strive for a level of brightness that would remain competitive into

PHOTOS 1 RENAN PICORETI – LNLS PUBLICITY / CNPEM **2** GLAUCIUS OLIVA / IFSC-USP **INFOGRAPHIC** ANA PAULA CAMPOS **ILLUSTRATION** ALEXANDRE AFFONSO

the future. “There wasn’t a machine with the characteristics they were suggesting in operation anywhere in the world,” recalled Silva on the morning of May 17, in his office at the LNLS. “It was our chance to get out in front of the United States, Japan, and the European countries, and stay there for a while.”

The LNLS teams returned to the design table and resumed equipment testing. Responsible for accelerator physics at the LNLS, Liu Lin and her group redesigned Sirius’s magnetic lattice so that its brightness would surpass that of the existing machines. Six months later, the committee approved the new project, budgeted at US$585 million (R$1.3 billion at the time). Obtaining stable financing was critical but only one part of the problem. “We had to acquire a location for construction and define the building’s characteristics while at the same time we were redesigning the machine and looking for a way around technological challenges,” Silva recalls. “There were times when we were juggling 20 plates in the air.”



Engineer Rafael Seraphim tests the vacuum system of the chambers that will propel the electrons. Left, quadrupole magnets, one of the components of the storage ring

The first R$9 million for the preproject were disbursed in 2009 and 2010 by the then Brazilian Ministry of Science and Technology (MCT), under the management (2005–2010) of physicist Sergio Rezende, who had first encountered Brum’s project in 2008. However, a definitive source of funding was missing, which would initially be provided by the MCT (now MCTIC, after incorporating Innovations and Telecommunications), together with the Brazilian Development Bank (BNDES) and other development agencies. Two other underwriters succeeded the ministry to lead the funding and contributed R$77 million to the project. Finally, in 2014, engineer Clélio Campolina Diniz was able to give the green light to begin construction with a proposed 2015 budget of R$240 million. The following year, Sirius was included in the second edition of the Growth Acceleration Program (PAC), which today is a Programa Avançar project.

Fluctuations in the dollar, inflation, and improvements to the light source and structural design elevated Sirius’s cost to R$1.8 billion. “It’s the only Brazilian project on this scale going forward without major delays,” says electronics engineer and physicist Rogério Cezar de Cerqueira Leite, chairman of the CNPEM board of directors, an NGO linked to MCTIC, the managing agency of the LNLS.

Pedro Wongtschowski, a chemical engineer who chaired the CNPEM board from 2010 to 2015, attributes the project’s adherence to its schedule and its low number of budget changes to the adoption of a governance model used by the private sector on large-scale projects. “Project execution only began once a detailed implementation plan was completed; the contracting of work was done through a careful bidding process, and the equipment that required longer delivery times was acquired first,” he recalls. “We also took advantage of the deployment of Sirius to develop components through Brazilian suppliers, a move that received support from FAPESP,” says Wongtschowski, current chair of the board of directors at Ultra (Ultrapar Participações) and a member of FAPESP’s governing council.

Of the total estimated cost, R$1.16 billion has already been delivered by the MCTIC, of which R$760 million was spent under the management of Gilberto Kassab, as noted by Cerqueira Leite, who played a fundamental role in the implementation of the UVX during the 1980s. In Leite’s view, Sirius only survived the recent economic slowdown because the project managed to gradually interest “authorities and politicians in Brasília,” in addition to its creators and the scientific community.

A similar conclusion was reached years ago by two researchers who analyzed the process of creation and implementation of the UVX. Léa Velho, a professor at the Department of Science and Technology Policy at the University of Campinas (UNICAMP), and Osvaldo Frota Pessoa Junior, a professor at the Department of Philosophy at USP, evaluated the reasoning that motivated the construction of the first Brazilian synchrotron and the negotiations that took it from design to real-

ally, which gave us the expertise used to create Sirius."

Building equipment to do science on a large scale demands a continuous flow of funds and technical and scientific expertise, and it almost always generates controversy. This was the case with the UVX project, and on a smaller scale, with Sirius. Soon after Brazil's first synchrotron light source project was approved, the directors of the Brazilian Society of Physics published a manifesto condemning the effort. It stated that there was not enough technical competence within the country to build it, that there would not be any users for it and that the UVX would drain resources from other areas of science and technology. "None of these predictions came true," says Rodrigues, coordinator of the Sirius accelerators. "We built the machine, the researchers came—today there are 6,200 registered users—and the level of funding has increased in every area."

"Large facilities like Sirius are expensive anywhere in the world, but they pay for themselves over time," says Fernanda De Negri, an economist at the Institute for Applied Economic Research (IPEA). Its cost represents 0.05% of the overall Brazilian national budget (government revenue), approximately R$3.5 trillion. "In many areas, infrastructure like this is necessary to producing quality science capable of generating innovation and making the country more economically competitive," the researcher says. In Negri's book *Novos caminhos para a inovação no Brasil* (New pathways to innovation in Brazil; Editora Wilson Center), she mentions Sirius as a rare example of long-term scientific planning in Brazil, launched in June.

"Since the atomic bomb project and the Apollo mission, science is no longer done only on small investments and short-term vision," says Glauco Arbix, a professor in the Department of Sociology at USP. Arbix is a former president (2011–2015) of the federal innovation promotion agency FINEP (Brazilian Funding Authority for Studies and Projects). He states that "It's necessary to have medium- and long-term vision, and to irrigate the system in such a way as to nourish smaller labs and create research projects with scientific, economic, and social relevance that are capable of raising the level of Brazilian science and increasing its impact. Without this, the country will continue to slip behind." ■

ity. In a 1998 article in the journal *Social Studies of Science*, they stated that support for the project came more from science policy sectors than from researchers and potential users. They added that the political skills of the few scientists involved were crucial to the project's implementation.

The hall where some of Sirius's experimental stations will be installed

"Sirius represents an attempt to leap to a new level of quality in Brazilian science," observes Argentine physicist Aldo Craievich. At the age of 79, retired from USP, he's still doing research using the UVX. Together with physicist Cylon Gonçalves da Silva and Ricardo Rodrigues, Craievich was the third member of the trio who coordinated the construction of the first Brazilian synchrotron.

The first large-scale research equipment project in Brazil—i.e., "Big Science," such as that which began in the United States during World War II with the nuclear bomb project—was initiated at the Brazilian Center for Physics Research (CBPF) in Rio de Janeiro in the early 1980s by physicist Roberto Leal Lobo and Silva Filho. With support from Lynaldo Cavalcanti de Albuquerque, then president of the National Council for Scientific and Technological Development (CNPq), Lobo guided the project until the beginning of the democratic government in 1985. With the creation of the MCT, he was replaced by Cylon, who had the support of the new agency's minister, Renato Archer.

"When we decided to build Brazil's first synchrotron light source, the only operational model that made sense was that of a national lab along the lines of US facilities, open to users from research institutions and companies in Brazil and abroad," Cylon notes. "The construction of the machine was merely an excuse to educate people who would be qualified to generate technology in Brazil, and capable of producing science at the frontiers of knowledge. We opted on designing and building as much as we could here nation-

Scientific article

VELHO, L. and PESSOA JR., O. The decision-making process in the construction of the Synchrotron Light National Laboratory in Brazil. **Social Studies of Science**. v. 28, i. 2, p. 195–219. April, 1998.

The race for the best light

Sirius will compete with a fourth-generation facility inaugurated in 2016 in Sweden and another planned to begin operating in 2020 in France

There is a rush to complete Sirius, Brazil's new synchrotron light source, which will be one of the most advanced sources in the world. The goal is to keep delays on completion of its construction and assembly to a minimum. It is currently a modest six months behind schedule, which is acceptable in a project of this magnitude and technical complexity. It's competition is just in sight. The facilities are designed to create a similar or even higher brightness than that of the Brazilian synchrotron, which will certainly attract the attention of academic researchers and companies interested in conducting experiments that require increasingly greater spatial and temporal resolutions.

This is why last May, while physicists and engineers from the National Synchrotron Light Laboratory (LNLS) completed the installation and performed the initial testing of the linear accelerator, workers and civil engineers were working on Sirius around the clock, from Monday through Saturday. They are working to finish the building by August so that other parts of the accelerator and the experimental stations can be assembled as soon as possible. Even if the facilities are ready in the near future, the new light source will not work without the connection between the high-voltage electrical grid and the substation that will feed Sirius and the rest of the campus at the National Center for Research in Energy and Materials (CNPEM), and this link has yet to be provided by Campinas-region utility CPFL Energia. Sirius and the campus together will consume the energy of a city of 40,000 inhabitants. "We need to hurry if we want to have the brightest light source in the world for even a short time," says physicist Antônio José Roque da Silva, director of the LNLS and manager of Sirius's construction.

Today, there are almost 50 synchrotron light sources operating in just over 20 countries. Almost half of them are concentrated in three countries: Japan has nine (many smaller sources), the United States has seven, and Germany has six. Just over 20 are third-generation sources, one generation earlier than the most modern equipment, which is now reaching the limit of what can be built. As a fourth-generation facility, Sirius will have two direct competitors: one light source that is already in operation in Sweden and another going into operation soon in France. There are also another 13 fourth-generation light sources being designed.

Located 500 kilometers south of Stockholm in Lund, Sweden, a city of 120,000 people, the MAX IV light source is the first in the world to be regarded as fourth generation. These devices are given this classification due to their innovative distribution of magnets around the electron storage ring, first proposed in 1993 by German physicist Dieter Einfeld and Slovenian physicist Mark Plesko in an article in the journal *Proceedings of SPIE*. This new magnetic lattice design was first adopted in MAX IV and allows smaller storage rings to be used to obtain more concentrated, brighter synchrotron light beams.

Built with components designed and manufactured in Sweden and other countries, MAX IV was inaugurated in June 2016 at a ceremony attended by the King of Sweden, Carl XVI Gustaf. The synchrotron consists of two storage rings: one containing electrons with 1.5 giga-electron volts (GeV), which feed two experimental stations currently in the commissioning phase, and a second with 3 GeV electrons, which provide synchrotron light for five stations, of

1

The European Synchrotron Radiation Facility in France, which will be upgraded in 2019 (*left*), and MAX IV in Sweden, the world's 1st fourth-generation synchrotron light source (*below*)

2

which three are active and two are in testing. "Since the start of operations, we've already had 318 users," says Brazilian-Swedish physicist Pedro Fernandes Tavares, MAX IV's director of accelerators. According to Tavares, the higher-energy ring should provide sufficient synchrotron light this year for the experimental stations connected to it to operate for approximately 4,000 hours, the equivalent of 167 days.

If everything goes as planned, Sirius and MAX IV will soon face a strong competitor: the extrabright source (EBS) of the European Synchrotron Radiation Facility (ESRF), located in Grenoble, a city of 160,000 people in the southeast of France, at the foot of the Alps. The EBS will be an enhanced version of their current synchrotron light source, which was the world's premier third-generation light source to go into operation, in the 1990s. The ESRF is operated by a consortium of 22 countries and, for the last three years, its technicians and engineers have been preparing for an upgrade, which will cost €150 million.

The current facility will be shut down in December of this year. Over the following 18 months, its storage ring will be dismantled and replaced by a new version with a circumference of 844 meters, which will provide electrons circling at 6 GeV of energy—double that of both Sirius and MAX IV. According to the ESRF communications office, the project is on schedule. It is expected that the new synchrotron, which will emit a brightness 100 times more intense than the current machine, will be reopened to users in 2020 and will provide beamlines to 44 experimental stations.

In the opinion of physicist Aldo Craievich, a retired professor from the University of São Paulo (USP) and one of the leaders in the construction of the first Brazilian synchrotron light source, the UVX, Sirius will compete on equal terms with MAX IV and the ESRF-EBS and attract international collaborators. "I am convinced that even researchers from the more developed countries of the Northern Hemisphere will come, because a good number of advanced experiments can only be done here," he states. "It will be a strong stimulus for international cooperation, which should exceed what the UVX did." The current Brazilian light source, which is to be shut down at the end of 2019, has an average of 1,200 users per year, with approximately twenty percent coming from other Latin American countries. ■ **Ricardo Zorzetto**

PHOTOS 1 ESRF 2 PERRY NORDENG