“In order to create such a large, world-leading scientific facility, many design challenges had to be overcome. Among these challenges were the very precise geometry required to house the accelerator systems, the unique structural features to achieve vibrational stability and meet shielding requirements, the grouping of lab and office facilities to optimize scientific productivity, the need for an expansive, economical, efficient yet attractive building envelope and finally, the need to have all these features work in harmony while achieving and exceeding sustainability goals.”

Martin Fallier
Facilities Division Director
Photon Sciences
Brookhaven National Laboratory
**Project Name**
National Synchrotron Light Source II (NSLS-II)

**Project Location**
Upton, NY

**Project Owner**
Brookhaven National Laboratory

**Date of Completion**
2014

**Total gross size (ft²/m²)**
600,000 ft² (55,472 m²)

- Ring Building: 393,000 ft² (36,511 m²)
- Lab Office Buildings: 207,000 ft² (19,231 m²)

**Total Construction Cost**
$301,000,000

**Total Project Cost**
$912,000,000

**Construction Cost per ft²/m²**
$501.67/ ft² ($5,426.16/m²)

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A new, cutting-edge facility at Brookhaven National Laboratory (BNL) is illuminating the path to scientific discovery. The National Synchrotron Light Source-II (NSLS-II), a third-generation synchrotron light source facility, is the newest and most advanced synchrotron facility in the world, replacing the original and recently decommissioned NSLS, also at BNL.

As a US Department of Energy Office of Science User Facility, NSLS-II will offer researchers from academia, private industry, and national laboratories unique tools and techniques to study material properties. Using super-intense synchrotron light, scientists will be able to unearth details at the micro and nano levels and watch, in real time, chemical and electronic processes that take place at the atomic scale. Ultimately, more than 4,000 researchers will use the facility annually, studying biology, chemistry, environmental science, materials science, medicine and physics.

NSLS-II will benefit the US economy and improve quality of life by providing state-of-the-art capabilities for x-ray imaging and high-resolution energy analysis. Work at NSLS-II will build on a foundation of important scientific discoveries that will enhance national security, advance modern medicine and produce abundant, safe, and clean energy technologies.
Research conducted at Brookhaven is published in more than 900 publications scientific journals annually. 7 Nobel Prizes have been awarded for its work.
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The Beam

The $912 million facility (including the beamline magnets and scientific equipment) will provide scientists with the world’s finest capabilities for x-ray imaging—delivering the brightest and most intense x-rays in the world—more than 10,000 times brighter than the original NSLS. NSLS-II generates light by accelerating a beam of electrons around a huge “ring” building at 99 percent of the speed of light. Nearly a half-mile in circumference, large enough to encircle Yankee Stadium, the medium-energy storage ring is designed to deliver world-leading brightness and flux at a resolution so clear that even a single atom will be identifiable.
The NSLS-II ring circumference is 792 meters (2,600 feet). The storage ring lattice—the arrangement of electromagnets along the path of the particle beam—consists of 30 Double-Bend Achromat (DBA) cells that enable 58 beamlines for user experiments. Multiple Insertion Devices (IDs) may be installed in a single straight section for additional beamline capacity.

Beamlines up to 72 meters (236 feet) long can be built within the ring building in sectors with the extended experimental floor width, as compared to 66-meter-long (217-foot-long) beamlines in sectors with the standard floor width. Extra-long beamlines of approximately 200 meters (656 feet) extending beyond the exterior walkway with endstations located outside the ring building are also possible.

The 58 beamlines that NSLS-II accommodates are distributed by type of source as follows:

- 15 low-beta ID straights for undulators or superconducting wigglers
- 12 high-beta ID straights for either undulators or damping wigglers
- 31 Bending Magnet (BM) ports providing broadband sources covering the InfraRed (IR), Vacuum UltraViolet (VUV), and soft x-ray ranges. Any of these ports can alternatively be replaced by a 3-Pole Wiggler (3PW) port covering the hard x-ray range.
- 4 BM ports on large gap (90 mm) dipoles for very far-IR
The
Machine

More than simply a building with labs inside, this 600,000 square-foot facility looks like, feels like and functions as a machine for science. The design mitigates vibration and heat fluctuations within an extraordinarily small margin of tolerance. Through the unique structural design and vibration isolating features integrated into the facility, the team met the design requirement of no more than 25 nanometers vibration in any direction—1,000 times more sensitive than what the human finger can feel. Temperature fluctuations, also crucial to the steadiness of the light beam, were designed to be controlled within 0.1 degree Celsius. As a result, the facility directly enables the science within.
First Floor Plan

- Main Lobby
- Berm
- Storage Tunnel
- Experimental Hall
- Service Buildings
- Access Corridor
- Lab Office Buildings
- Support Space (Radiofrequency Building, Booster Building, Klystron Gallery, Compressor Building, Cooling Tower, Loading Dock)

Legend:
- Orange: Main Lobby
- Green: Berm
- Blue: Storage Tunnel
- Purple: Experimental Hall
- Beige: Service Buildings
- Brown: Access Corridor
- Yellow: Lab Office Buildings
- Gray: Support Space

Annotations:
- PENTANT 1
- PENTANT 2
- PENTANT 3
- PENTANT 4
- PENTANT 5
- EXTRA-LONG BEAMLINES

Other:
- LOB 1
- LOB 2
- LOB 3
- LOB 4
- LOB 5
“We studied the geometry of the ‘machine’ and developed a structural grid with column lines angled at three degrees apart. This mirrors the angle of the accelerator beamline as it bends, while passing the various magnets in the storage tunnel. The geometry of the conventional facilities mirrors that of the accelerator.”

Ahmad Soueid
Senior Vice President
HDR
Storage Tunnel and Booster

NSLS-II is a medium energy (3.0 GeV, or 3-billion-electron-volt) electron storage ring designed to deliver photons with high average spectral brightness exceeding 1021 ph/s in the 2 – 10 keV energy range and a flux density exceeding 1015 ph/s in all spectral ranges. This performance requires the storage ring to support a very high-current electron beam (I = 500 mA) with a very small horizontal (down to 0.5 nm-rad) and vertical (8 pm-rad) emittance. The electron beam will be stable in its position (<10% of its size), angle (<10% of its divergence), dimensions (<10%), and intensity (±0.5% variation).
Typical Section, Ring Building
Magnets

826 high-precision magnets form the main accelerator ring of the NSLS-II. A beam of electrons shoot through the center of each magnet, where powerful magnetic fields contain and steer the particles in a nearly circular path. Light emitted by electrons traveling around the ring will be shunted to beamlines, a collection of scientific instruments where experiments will be conducted.

NSLS-II radiation sources span a very wide spectral range, from the far infrared (down to 0.1 eV) to the very hard x-ray region (>300 keV). This is achieved by a combination of Bending Magnet (BM), 3-Pole Wiggler (3PW), and Insertion Device (ID) sources.
Experimental Floor

Beamlines are deflected to the experimental floor, which is built for vibration stability to preserve the integrity of the beam. Space on the floor is occupied by various tenants, and depending on the experiment, the amount of space—and the length of the beamline—varies. Overall, the circumference of the experimental floor is approximately a half mile. (A person cannot perceive the entire space from any one spot on the floor). Because it is so long, researchers and technicians make use of large tricycles to navigate the floor. The beauty and elegance of the exposed, precise engineering, as well as the sheer volume, creates a sense of awe. It is a spectacular, active hub of science—and a tribute to innovative and meticulous engineering.

Research at NSLS-II focuses on some of our most important challenges at the nanoscale.
Molecular Electronics
The facility will allow scientists to observe fundamental material properties with nanometer-scale resolution and atomic sensitivity, making faster and cheaper electronics that consume less power.

Self-Assembly
NSLS-II will allow scientists to create connections between large-scale hierarchical structures and nanometer-scale building blocks, enabling them to assemble nanomaterials into useful devices more simply and economically.

Clean and Affordable Energy
By imaging highly reactive gold nanoparticles inside porous hosts and under real reaction conditions, NSLS-II will lead to new materials to split water with sunlight for hydrogen production and harvest solar energy with high efficiency, at a low cost.

High Temperature Superconductors
The facility will allow scientists to study how materials become high-temperature superconductors, which may lead to the efficient transmission of electricity.
Exterior

The exterior of the ring building is appropriately and simply clad in metal panels that reinforce the sweep of the circle and creates a simple envelope for the “machine” inside. The simple and functional exterior is an intentional contrast to the complexity of the engineering inside.

A vehicular access tunnel extends from the exterior to the interior of the ring, below the electron storage ring. (Occasionally, deer must be escorted from the interior of the ring back through the tunnel to the exterior.)

Inside, the enormity of the ring is apparent. Yankee Stadium would easily fit inside. Located inside this area, the booster building houses the injection system for the electron accelerator in the storage ring, and includes the electron gun, Linear Accelerator (LINAC), and the booster ring. The cooling tower is located inside the ring, providing cooling for the primary deionized water system.
Visitors’ Entrance

The main or visitors’ entrance to NSLS-II is a two-story, mostly glass “box” leading to the experimental floor. It is awash with daylight: a welcoming spot for touring groups, educational outreach programming, and social functions. It includes a communicating stair and elevator that leads to the “bridge” over the experimental floor to the ring tunnel mezzanine. The bridge affords the most expansive views possible of the experimental floor—much like the balcony level in a gothic cathedral.
Lab Office Buildings

The goal of the Lab Office Building (LOB) design was to optimize the space available for users and beamline support staff to get the highest productivity out of each beamline.

Each of the five identical LOBs features 11 labs, with a mix of wet labs, dry labs, fabrication and assembly shops, and tech spaces with easy access to the experimental floor. The LOBs also include a shipping, receiving and storage area with roll-up door and rolling access to the experimental floor. Laboratories are located adjacent to the ring building where the beamline experiments will occur. Each LOB has offices designed for up to 124 occupants, with a mix of single-person and multi-person hard-walled offices and open-plan soft-walled offices for flexibility. Clerestory windows drench the open-plan offices with natural lighting, and extend above a central lobby area for gatherings, displays, and informal interaction space.

The detailed design of the LOBs took into account the feedback and recommendations of beamline groups and advisory committees. Detailed layouts of each lab and office were developed to assure the right type and amount of space was provided to support beamline operations.
Construction

To simplify construction and expedite occupancy, the ring building was designed as five equally spaced, identical sectors. As the contractor finished each sector, the client could move in and begin installing beam-line magnets. The contractor phased the work and built temporary walls to separate finished sectors from construction—providing temporary heat during winter months. The first sector was completed over a year before the remainder of the building, allowing Brookhaven to begin its work ahead of schedule.

To calculate the precision necessary for installation of the beamline components, alignment monuments like this one inside the ring were used, as well as an alignment monument at the center of the ring.
The suitability of the site was just as critical as the design precision. Structural sand was placed in six-inch lifts, ten feet below the surface of the ring building’s footprint, compacted with vibrating rollers and tested with nuclear density compaction testing equipment. The more traditional approach of driving piles into the earth for building stability was not a viable option for NSLS-II due to the vibration it would produce, which could ruin ongoing experiments at the lab.

Additional numerical models helped examine the service building locations with respect to the ring, and placement of equipment within those buildings. Placing service buildings inside the ring with structurally supported floors (rather than a slab on grade) will dramatically reduce the level of vibrations felt by the beamline.

This one-of-a-kind, precise design delivered a pioneering facility with the engineering innovation needed to accomplish the specific vibration and temperature fluctuation requirements for the world’s finest x-ray imaging capabilities.
By working closely with Brookhaven’s scientific community, designers developed numerical models to give this 600,000-square-foot facility the precise design criteria needed to achieve the US Department of Energy’s goals. With the electron beamline as the focal point, the models determined the thickness of the concrete slab below the beamline and throughout the facility, the advantages of a structurally monolithic concrete pour, where to locate the machine rooms, and even what types of pumps and fans to install.

A total of 41,000 cubic yards of concrete was poured (a single, monolithic pour involving 4,000 concrete trucks over 18 months) to form the 27-inch slabs, up to 39-inch walls and 32-inch ceiling that make up the accelerator tunnel. Numeric models indicated the the optimal combination of concrete thickness in the tunnel floor, wall and roof sections, combined with distance and isolation of machinery spaces to achieve effective attenuation and filtering of vibration sources. Compacted sand below the slab eliminates settling—maintaining the tight tolerances necessary to keep the beamline from moving.

Numerical models identified the maximum allowable thermal gradients and the level of temperature control needed to assure beamline stability. The cooling tower and five service buildings were designed with 1,800 tons of cooling tower capacity and 2,500 tons of mechanical refrigeration. Redundancy was designed into the beamline cooling system by having twice the required HVAC equipment installed, and two emergency generators are provided for life safety and smoke control.

Original or Innovative Application of New or Existing Techniques

Imagine having the ability to view a single water molecule with such clarity that hydrogen and oxygen atoms could be magnified and separated—harnessing hydrogen fuel from water. This is only one example of the research that will be performed at the new NSLS-II. Enabling researchers to view a single atom—with more clarity than ever before—is possible because the beam doesn’t move—a result of the facility’s ability to hold vibration and temperature fluctuation to an unprecedentedly small range of tolerance.
Sustainability

The project incorporated a large number of sustainable design features. The ring building and the five LOBs have been awarded LEED Gold certification.

The facility has dedicated parking for bicycles, fuel-efficient vehicles and carpools. The site includes 30 acres of open green space, with native plants not requiring irrigation on 50 percent of the site, saving water. Within the ring building, low-flow fixtures achieved a water savings of 37 percent, with a 40 percent savings for the LOBs.

The facility demonstrates significant energy savings, with the cooling towers reducing central plant cooling energy by an anticipated 1.2 megawatts annually. Other energy efficiency measures include an improved thermal envelope, high efficiency glazing and motion sensors and timers reducing the amount of lighting energy expended. A commissioning contractor assured accurate operation and performance of all systems.

Additionally, 87 percent of construction waste was diverted from landfills. Both the design and construction activities also had to address construction debris and silt runoff into the surrounding wetlands, which were monitored and mitigated. Environmental issues with endangered species such as the Tiger Salamander living near the 50-acre site were monitored as well.
The Future

The precision of the NSLS-II design is unprecedented, demonstrating the level of detail needed to create a facility with such specific scientific requirements. The lessons from this design will not only benefit construction of future scientific facilities, but they also create public awareness through the highly publicized research that occurs at Brookhaven National Laboratory.

Research at the facility affects a broad range of topics around the world, drawing attention to its unique capabilities. The quality and strength of synchrotron light cannot be produced by conventional sources of light. With the commissioning of NSLS-II, even nanoscale details will soon be accessible. Peering this far into materials is not possible in conventional laboratories.

The unique tools, research techniques and support offered at NSLS-II are ideal for industrial scientists and researchers who would like to find solutions to scientific or engineering problems faced in their own laboratories, broaden their research interests and enhance existing research programs. Performing experiments using properties of synchrotron light can be incredibly useful and beneficial to commercial industries, from biotech to renewable energy, from microelectronics to pharmaceuticals. NSLS-II will assist private companies in ways never known possible—and, ultimately, become more innovative, competitive, and profitable.

The widespread impact of NSLS-II will bring attention to the facility’s cutting-edge design, which makes advanced scientific discovery possible.
We practice increased use of sustainable materials and reduction of material use.