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Physics in Perspective

The National Synchrotron Light Source, Part II: The Bakeout

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This is the second part of a two-part article about the National Synchrotron Light Source (NSLS), the first facility designed and built specifically for producing and exploiting synchrotron radiation. The NSLS, a $24-million project conceived about 1970 and officially proposed in 1976, had its groundbreaking in 1978. Its construction was a key episode in Brookhaven's history, in the transition of synchrotron radiation from a novelty to a commodity, and in the transition of synchrotron-radiation scientists from parasitic to autonomous researchers. In this part I cover the construction of the NSLS. The story of its construction illustrates many of the tensions and risks involved in building a large scientific facility in a highly politicized environment: risking a facility's quality by underfunding it versus asking for more funding and risking not getting it; focusing on meeting time and budget promises that risk compromising machine performance versus focusing on performance and risking cancellation; and the pros and cons of a pragmatic versus an analytic approach to commissioning.

Key words: Martin Blume; Samuel Krinsky; Arie van Steenbergen; Brookhaven National Laboratory; National Synchrotron Light Source; synchrotron radiation; accelerators.

Groundbreaking

Fall 1978 was heady at Brookhaven National Laboratory (BNL), one of the most upbeat periods in its history. In less than a month, ground was broken both for the lab's new high-energy accelerator, ISABELLE, and for its new solid-state (albeit interdisciplinary) physics facility, the National Synchrotron Light Source (NSLS).

The NSLS groundbreaking took place on September 28 (figure 1). A few visitors and some lab personnel noted that its small crew of builders were less enthusiastic than was usually expected and exhibited on such a celebratory occasion. "It was hard to get festive when we faced what was obviously a whole lot of problems and constraints," recalled John Galayda, one of the accelerator physicists. Still, Project Director Arie van Steenbergen managed to get expansive, telling the audience that "when God said 'Let there be light!' that light was synchrotron radiation." He meant, presumably, that virtually all of the light accompanying the Big Bang was radiation from charged particles. The ceremony symbolically culminated with Don Stevens, Director of the Division of Materials Science of the Department of Energy (DOE), digging up a preplanted wood-

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Fig. 1. The groundbreaking for the NSLS on September 28, 1978. Wielding the shovel on the left is Arie van Steenbergen, and on the right is Don Stevens. *Credit*: Brookhaven National Laboratory.

en $h\nu$ symbol – the expression for the energy of a photon, h being Planck's constant and ν the frequency.

Both ISABELLE and the NSLS would soon be in serious difficulty, though for different reasons. ISABELLE's problems stemmed from a flaw in the ambitious superconducting braid of its magnets.[1] These would require a technological fix, though the need would only begin to dawn on its builders a year after groundbreaking. The NSLS's problems arose because its budget was inadequate, which was widely known already at the time of its first "Schedule 44" submission in 1975 – and it was also known to all that this had been a condition for the approval of the project in the first place. The thought, again, was that the facility would be like a handyman car – if you can get one on the cheap, you can use it while slowly putting in better parts as you can afford them. Better than no car at all, right?

The handyman-car strategy would have been difficult to pull off in any case, given how underfunded the machine was. Several additional factors made the task even more challenging. First, the funding profile: While the NSLS, unlike ISABELLE, was awarded its full requested budget of $24 million, the monies were spread out unfavorably, with only $5 million rather than $11 million awarded in the first year. This required stretching out construction over 4 years (1978–1982) but without additional funds to cover manpower in the final year. Second, raging inflation, on the order of 12% annually, further cut into resources. Third, the NSLS's builders would discover (as Ken Green had anticipated) that high brightness posed unanticipated demands on a machine, which translated into the need for more money. Economies aplenty had already been made in the design; more would be required during construction.

Much of the challenge would be addressed through simple hard work. Here van Steenbergen set a demanding pace. He never walked slowly, but always at a fast clip or even a trot. "There goes Arie!" one often remarked as the man breezed past in the third-floor corridor of Building 911 without pause for hello. Van Steenbergen hated ordinary meetings, which wasted time and tended to wander into unnecessary topics. He preferred to solve a problem by grabbing the appropriate person or two for a brief consultation in one of the tiny rooms on the Alternating Gradient Synchrotron (AGS) third floor known as "cubby holes," giving rise to a particular style of meeting at Brookhaven that, throughout the lab, came to be known as a "Cubby Hole meeting." He arrived early, stayed late, and ate a simple dinner in his office. Hank Hsieh, the Chief Engineer of the NSLS, often left at 10:30 or 11:00 at night, and recalls always preceding van Steenbergen. Galayda would break for dinner, put his children to bed, and then return until 1 AM, and occasionally sleep in his office. Everyone worked on weekends and most holidays. At the convivial Christmas parties, secretaries collected food to take down to the scientists working on the machine. Visitors to the laboratory often remarked that, late at night when the rest of the buildings in the laboratory were almost all dark, the third floor of Building 911 was always ablaze with light and activity.

But the continual need to make tradeoffs in a shrinking budget (and a too-small building) would introduce problems that would affect all subsystems of the machine. It also produced tensions between van Steenbergen and the small crew of other inhabitants of the AGS building's third floor. The conditions that had set the stage for these tensions were not van Steenbergeen's fault, but had been created by the unstated agreement with the lab management and the DOE to overlook the machine's underfunding and accept the budget. Van Steenbergen, in fact, had asked BNL Director George Vineyard to raise the budget for the machine, but his request had been denied in no uncertain terms. And as ISABELLE's problems worsened, Vineyard's position that the NSLS must come in on time and on budget hardened. In view of the subsequent conflicts and machine difficulties, therefore, it is important to remember that in effect impossible demands had been placed on the accelerator builders.

"We begged, borrowed, and stole what we could," said NSLS accelerator physicist Richard Heese. "We were a talented bunch, OK? We had good people. We were imaginative, we were clever, we knew how to find things second-hand. We did a lot of the ground-breaking work that had to be done to build the first dedicated high-brightness light source. We did the best we could. But the problems were too much."

Construction

Van Steenbergen's approach to building the NSLS emulated Robert R. Wilson's in building Fermilab. One of van Steenbergen's strengths was that he, like the Fermilab leader, drove his project hard, at least in its initial stages. Another was his fortitude: he was able to withstand shocks to the system without reducing momentum. This was an important trait in view of the many shocks that the NSLS project would suffer. Truth to tell, however, Arie van Steenbergen was no Robert R. Wilson, and he had certain limitations that Fermilab's leader lacked.

One had to do with van Steenbergen's experience with accelerators. His intuitions had been shaped by experience with the AGS, a synchrotron. An electron storage ring used as a dedicated light source was a much different animal, however, and would put demands on magnet placement, precision in the power supply, and vacuum quality that were not required of proton synchrotrons. Van Steenbergen not only lacked experience with dedicated synchrotron-radiation sources – as did everyone else at the time – but also lacked sufficient insight into accelerator fundamentals to appreciate early enough how much the new demands had altered the ground rules.

A second limitation had to do with personal character. Like Wilson, van Steenbergen liked to look over everyone's shoulder and have the final say on all decisions. He was "a spider in the middle of a web, who pulled all the strings," as one scientist put it. Contributing to his authority was that van Steenbergen served both as project manager and as chief accelerator physicist. Yet, he was unable to listen to his subordinates when he needed to. "He was stubborn, though not malevolent," said one subordinate. "He wouldn't try to kill you, only to win. Sometimes it was just too exhausting to fight with him."

Both limitations had unfortunate consequences for the NSLS. The $24 million was insufficient. Still, if one were set upon making that goal anyway, there were better and worse ways to go about making the often-painful compromises, and the better ways suggested by junior staff members sometimes were not chosen. Some standard equipment, including certain types of beam instrumentation, was not installed, and some essential procedures, such as a highly accurate survey, were not carried out. Tradeoffs had to be made that would hamper performance. But they were sometimes done in a way that could not be improved by subsequent upgrades, rather than being carried out in a way that allowed for that possibility.

Van Steenbergen, in short, was determined not only to build the handyman car, but both on schedule and on budget, and to do so was willing to make compromises that others felt were unacceptable. He already had made such compromises, in ways that had aroused conflict, in decisions about the magnet size, the lattices, and installation of parts; more conflicts would erupt during construction. He was more diligent than many lab administrators secretly hoped. When lab officials asked "Is Arie on budget?" the stock and only half-joking answer often was, "Yes, unfortunately."

Samuel Krinsky, the accelerator physicist who had worked with the NSLS project the longest, was forthright in pressing for the optimal design and construction, and avoiding unnecessary compromise – "Krinsky was the conscience of that machine," in the words of one colleague. That conscience took a beating in the form of the need to meet the bottom line, embodied by van Steenbergen, who was equally forthright in his focus on holding down costs and pushing the schedule. The resulting conflicts were often fundamental and fierce.

"Sometimes I'd threaten Arie that if he did that, I'd leave the project," Chief Engineer Hsieh said. "These threats were over serious issues, and I meant them. But on a big technical construction project, big arguments are a part of how the job gets done. We had respect for each other. It was a big hardworking family."

Building

Completion of the NSLS building, the normally implacable van Steenbergen once wrote in a memo, was "appallingly slow," with the contractor providing "a litany of promises and excuses" that ran on for almost two years.[2] The delay further cut into the budget by forcing him to spring for installation of temporary water, heating, and air-conditioning systems, and to pay staff overtime. Pieces of each system – including the magnets, power supplies, vacuum, radiofrequency (rf), and control systems – had to be built either in separate labs or in available spaces around the lab while the building construction continued. The vacuum system, for instance, was built in Building 535, which in earlier periods of lab history had housed a bowling alley, a bomb shelter, and various neutron-source experiments. Frustrated scientists and engineers moved in right behind the construction workers as they finished each section of the building, a practice legitimized by the euphemistic technical term "beneficial occupancy." But the scientists and engineers often had to work underneath tents made of plastic warmed by space heaters, and the condition made wags such as Galayda joke antonymically about what "detrimental occupancy" might mean.

Magnets

The bending magnets, for both the UV and X-ray rings, as well as the Booster, were made by gluing or laminating together C-shaped pieces of steel sheets. These were in the form of a C-shaped parallelogram, a millimeter thick, about a foot and a half or so wide, and about two feet high. The thinness of the laminations would make the magnets easier to produce, and also would reduce eddy currents in the Booster, which would have to be quickly ramped (to ramp a magnet means to increase its field strength). A quarter of a million of these cutouts would have to be industrially stamped and brought to Brookhaven for assembly.

In principle, producing the laminations was a routine industrial process: Coils of steel are unrolled into a set of leveling rollers to be flattened, then fed into a stamping machine to be punched out by a press using a precut die. Hsieh located a tool-and-die firm in Camden, New Jersey, called Haddon Tools, that was stamping laminations for the Positron Electron Project (PEP) at Stanford. A contract was signed, and the company began stamping NSLS laminations in 1978.

But economies created more problems than expected. Because the main rings of the NSLS, unlike the AGS, were storage rings, and did not need to be ramped as quickly or

– in the case of the UV magnets – even at all, the dipoles for the NSLS did not need to be made of as high-quality steel as those of the AGS. Thus, while the AGS dipoles were made of silicon steel, van Steenbergen felt safe ordering the NSLS dipoles to be made of inexpensive steel of the sort used to make appliances such as washing machines, as long as the carbon content was low enough. It was – but during the rolling process the temperature had not been uniformly controlled, affecting the hardness of the steel, which now varied from roll to roll. In the punching process, this turned out to affect the gap dimension, which varied sometimes up to 15 mil (millionth of an inch), depending upon which roll the lamination had been stamped from, as well as the gap structure, since the pole pieces were sometimes not parallel. The result was not within the tolerances of the drawings. "None of us had ever experienced this," recalled Hsieh. "When we discovered it, we sat there with our mouths open."

Then came a worse disaster. In the early fall of 1979, Hsieh received a phone call from a PEP colleague complaining that Haddon was not only producing poor-quality laminations, but that their production rate was plummeting. Fortunately, Haddon had just finished stamping the PEP laminations – but the PEP colleague advised Hsieh to pay attention to the Brookhaven job, which had just begun.

Hsieh, van Steenbergen, and an engineering student named Payman Mortazavi then drove to Camden to talk to the owner of the company. The owner explained that the company was about to go bankrupt, all stamping had stopped, the matter was out of his hands, and a liquidating firm would shortly take possession of the factory and lock the doors while an auction of the goods and equipment inside was arranged. The three argued furiously with the owner, but to no avail.

It looked like a disaster – maybe even the end of the NSLS. To recontract the stamping would delay the machine by at least a year, at considerably higher expense in addition to the funds already paid to Haddon and now lost. But Hsieh had an idea. When he returned to Brookhaven he first asked Krinsky and Galayda whether – given the undesirable variations in gap size and pole-piece structure – it was even possible to use the Haddon laminations. After extensive analysis, the two decided that it was, provided they were suitably shuffled so that the average gap of each magnet was the same. Hsieh then drove back to the factory. By now the liquidating company had taken over, and it had appointed a representative to oversee the now-locked plant and arrange the auction of its equipment. Hsieh then appealed to the representative. Hsieh was Chinese, the representative was Hawaiian: both were in appearance racially out of the mainstream in Camden, New Jersey. Hsieh played up this slender bond as much as he could while explaining his situation. He concluded with a personal appeal to the representative, placing the emphasis not on how critical this was for the laboratory, but rather on how difficult a situation it was for he, Hsieh, personally. He asked the caretaker to postpone the auction of the stamping machine, and to close his eyes and look the other way while Hsieh came in with a handful of Brookhaven's mechanical technicians for several weeks.

Amazingly, the caretaker agreed. "He responded out of the goodness of his heart," Hsieh said. "And because he was the only one there it was possible."

Hsieh drove back to Brookhaven, recruited about half a dozen technicians, and took them back to Camden. They rented rooms in a nearby hotel – two people to a room to save money, which was a cause for griping. When they showed up at the Haddon factory, the representative let them in. Hsieh had never worked on such a big and complex (450-ton) industrial machine. Nevertheless, his technical staff was able to figure it out and resume production. For six weeks in fall 1978, Hsieh and the Brookhaven crew ran the machine furiously, the machine going "K'tonk! K'tonk! K'tonk!" every six or seven seconds or so as it punched out the laminations, working two shifts (16 hours) a day, 5 days a week for 6 weeks, with downtime for loading new coils of steel into the machine and machine maintenance.

When they finished, just before Thanksgiving, the Brookhaven employees packaged the laminations on pallets by coil (to help identify the approximate gap size), loaded them onto a flatbed truck, and drove them back to Brookhaven. Rarely has the success or failure of a major facility depended upon such a personal encounter.

The laminations were delivered to Building 919, the old 7-foot bubble-chamber building, where they were glued into 8-inch blocks and cured in a homemade oven (there being no money for an industrial one). These blocks were then sorted by gap size, put on a table, clamped together, and fitted with coils. The dipole coils were made by Everson Electric Company; the coils for all of the other magnets – the quadrupoles, sextupoles, wiggler magnets, and correction magnets – were made at Brookhaven, under Hsieh's guidance, to save money. During the coil manufacturing, van Steenbergen could not afford to hire any additional permanent technicians but rather used job shoppers with no experience making coils, and had them trained at Brookhaven for their few weeks of work. "The light source owes these job shoppers a lot," Hsieh said; many became so adept that they stayed around to become permanent employees of the laboratory.

After being fitted with coils, the magnets were moved to Heese's test lab in the same building, located in a separate room with a hole in the roof so that a crane could drop them into place. Heese did an extensive set of magnetic measurements using a Hall probe on a rectangular grid of 5 millimeter spacing, and to an accuracy of 1 gauss out of 2,000 gauss. These measurements were subsequently used by NSLS accelerator physicist Roy Blumberg to obtain a 62-parameter representation of the three-dimensional magnetic field. The magnets were then delivered to the NSLS floor.

Linac

The 70-MeV (million-electron-volt) Linac was constructed in Building 925, near the AGS, which had been used to assemble electrical components in ISABELLE's early stages. "Funding limitations prevented acquisition of a state-of-the-art system," a later report delicately says, and the Linac was cobbled together out of second-hand parts, most of them twenty years old, from different laboratories in the United States and abroad. The electron gun, along with support girders and other equipment, came from the Cambridge Electron Accelerator (CEA), operated jointly by Harvard University and the Massachusetts Institute of Technology (MIT). The two accelerating cavities came from an accelerator at the Institute for Nuclear Physics Research (IKO) in Amsterdam. The klystrons, which produced the radiofrequency (rf) pulses for the cavities, were rejects from the Stanford Linear Accelerator Center (SLAC); they had not met specifications but were still serviceable. The special modulators that powered the klystrons – the pulsed-power generators that are set at a low voltage, slammed on full for a short time, and then backed off – came from the AGS.

Many of these second-hand parts had flaws. The worst was a water leak inside one of the IKO cavities. This was considered a crisis when it was first found, for the project could not afford a new cavity and the leak was extremely difficult to repair given the particular way the cavity had been put together. The machinists in the heavy-machine shop took a gamble, guessed where the leak might be, and made an incision in the steel jacket. Fortunately, they guessed right, and were able to fix the leak while keeping the cavity operable.

"The Linac was built with string, scotch tape, and bailing wire," Heese once said. This was not entirely a joke. On a recent tour, he pointed out a tiny steering magnet near the electron gun that was still partly affixed with scotch tape. "The Linac worked, poorly, but with a lot of tweaking we managed to get some current out of it."

Brookhaven's accelerator engineers, used to handling heavier particles, initially underestimated the shielding requirements for electrons. They installed shielding on the inside but not on the outside of Building 925, failing to appreciate adequately that when electrons stop in matter they produce showers, creating high-energy gamma rays. A guard had to be stationed in the parking lot outside the building to keep people from walking past when the machine was turned on for testing.

Booster

Economies were made on the Booster in the form of a smaller size and simpler lattice.[3] The number of kickers – which nudge or "kick" the beam during injection into one of the bigger rings – was reduced from four to three, which slowed the charging rate and made it harder to control the beam. The kicker chambers were secondhand CEA parts, and extensive work was required before they were usable. Simpler high-voltage equipment was ordered instead of state-of-the-art equipment. One set of power supplies was ordered for the two transfer lines. This seemed reasonable, for the Booster could charge only one ring at a time. But it was unwieldy in practice, since the power supplies had to be readjusted each time the injection was switched over from the UV to the X-ray ring or vice versa – which led to reproducibility problems that slowed the charging even more. And somehow the UV ring-Booster connection was misplaced, meaning that a building I-beam support had to be cut through, and a transfer line had to be made more curved than planned. Finally, when the first magnet measurements were obtained, they indicated that the dipoles should be shifted over a few millimeters for optimum tuning of the beam. But the support holes already had been drilled in the floor, and rather than spend the time and money to redrill them, the magnets were left in their less-than-optimal positions.

Impact of ISABELLE

The first ring magnets to leave Building 919 for the NSLS building were delivered to the UV ring on December 31, 1979 (figure 2), and van Steenbergen, Hsieh, and engi-

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Fig. 2. The delivery of the first magnets for the NSLS on December 31, 1979. *Left to right*: Hank Hsieh, Arie van Steenbergen, Jules Godel. *Credit*: Brookhaven National Laboratory.

neer Jules Godel spent most of their New Year's Eve installing them on the still-unfinished floor. Within a few months, the UV magnets and vacuum system were fully installed. In July 1980, the Linac was dismantled from Building 925, moved to the NSLS building, and reassembled, producing a meager beam in September.

The UV ring, smaller and less complex than the X-ray ring, was the first of the two completed. It had more forgiving tolerances, and the beam did not need to be accelerated. Nevertheless, economies throughout the machine hurt. Its second-hand copper-clad rf cavities were difficult to weld without introducing leaks, and had to be reworked.[4] And while the design called for five vacuum pumps per superperiod (a repeating segment of the lattice), only three were bought and installed, which diminished the beam current.

But by the time the first injection studies from the Linac into the Booster were made in November 1980, troubles had broken out on the ISABELLE project,[5] and in trying to solve them lab administrators were so desperate that they raided even the skimpy resources of the NSLS.

Progress on ISABELLE had been slow since 1979, though Brookhaven's administration maintained an upbeat public face until the fall of 1980. Until then, the ISABELLE magnet division was still working only one shift; on weekends, van Steenbergen noted with scorn and annoyance the emptiness of its parking lots. Prodded by the DOE, Vineyard made some administrative changes. These included making Nicholas Samios Associate Director for High Energy Physics, and Martin Blume Associate Director for Low Energy Physics and Chemistry. Vineyard also reshuffled some laboratory resources, cannibalizing in favor of ISABELLE where he could. This included ordering Hsieh to leave the NSLS to become Ronald Rau's deputy for engineering ISABELLE's braid superconductor. That was a terrible blow to the NSLS. Hsieh had a tiny crew of three assistants, but knew how to set them to work.

Hsieh had overseen the installation of the Booster, Linac, and UV ring, and was in the middle of installing the X-ray ring – his main challenge on the project and what he had most looked forward to. Twenty years later, he still recalled the day he left the NSLS for ISABELLE, walking sorrowfully past the completed UV ring and through the partly-completed X-ray ring – "my baby," he called it – with a few dipoles atop girders. Van Steenbergen began to call the "other" lab-accelerator project "Jezebel," after the wicked character played by Bette Davis in the eponymous 1938 movie, who did "bad things" to her man.

The NSLS project continued for a time without a chief engineer, though Hsieh lent help clandestinely when he could. In his absence the Linac was attached to the Booster and attempts were made to coordinate the two. Neither was working well, because it was a machine built from cut corners, and because of the circumstances under which the commissioning was taking place. As Galayda recalled:

> We did a lot of stuff it's hard to be proud of. We started commissioning the Booster without heat in the building, and without ramping power supplies. And the equipment was terrible. I can remember, for instance, spending a night with the wrong energy Linac beam. I had set up a computer program that would tell me, based on the beam positions in the Booster, if the magnets were at the right settings or not. I just didn't believe it when the program began telling me that the energy of the Linac beam was way off from what it was supposed to be. But it turned out to be right; the equipment was bad. That was quite a night. Then I spent weeks – day in and day out, with breaks only for food and sleep – to ramp the Booster, only to discover that the culprit was unexpected eddy currents. I learned a lot of things they didn't teach in graduate school.[6]

The beginning of summer 1981 was a low point for the laboratory, in sharp contrast to the upbeat spirit of just three years earlier. The braided ISABELLE magnets could not be repaired, causing the entire project to lose momentum. The project seemed, even to many at Brookhaven, to be on its last legs. At the NSLS, the Linac was performing poorly and the Booster could only reach 400 MeV at a low current. The UV

Fig. 3. The NSLS employees raising their arms in triumph outside of the NSLS building when the first beam was obtained in the UV ring in August 1981. *Credit*: Brookhaven National Laboratory.

ring had been essentially completed for over a year with no detectable beam, and the X-ray ring was not even ready for beam. Interest in synchrotron radiation was high – in June 1981 *Physics Today* devoted a cover story to synchrotron radiation with a photo of Brookhaven's UV ring on its cover. But the NSLS was nowhere near ready for experimentation. Another serious blow was Heese's departure. He had decided to return to Canada because of a mixture of personal problems and frustration with the project.

UV Ring

When the first beam in the UV ring was detected in August 1981 – though at a very low intensity – lab administrators seized on it as cause for celebration. NSLS employees were marched outside and had their pictures taken outside the building, their arms raised in triumph (figure 3). A subset had their pictures taken in the control room (figure 4).

Again, those working on the machine were the least enthusiastic of the celebrants, for they had a taste of how difficult the ensuing commissioning would be. The UV worked, but not well, and it was clear that the main power supply of the Booster had to be rebuilt before the injection could reach the design capacity of 600 MeV. This effort was hampered because, by now, the X-ray ring was behind schedule, and all available manpower was being sent in that direction. And when the Linac-Booster-UV system was turned on again in the fall, though the Booster was now able to reach 600 MeV, the engineers could not detect the beam in the UV ring. A major reason, it soon surfaced, was poor instrumentation and trapped ions, which the engineers struggled to

Fig. 4. A group of NSLS employees in the control room of the UV ring when the first beam was obtained in August 1981. Accelerator physicist John Blewett has his left hand on the instrument on the right, Arie van Steenbergen is pouring the champagne. John Galayda is down in front in the striped shirt, Sam Krinsky is second from left in glasses, Payman Mortazavi is fifth from left standing in front of Krinksy, Joe Sheehan is at top. *Credit*: Brookhaven National Laboratory.

control. The scientists were so depressed that they considered canceling the traditional Christmas party. By this time they were already compiling ideas for replacing parts and expanding the experimental facilities, with the idea of eventual consolidation into a construction proposal of its own.[7]

Then, on the Friday morning before Christmas 1981, the scientists managed to detect a long-duration beam. A day later, they achieved a synchronized rf capture and had a circulating beam with a lifetime of about 2 minutes, with accumulative charging of the UV storage ring from the Booster. The ring was still unusable for experimentation, but it was a start.

The principal source of beam loss in the UV ring at this point was collisions with outgassed ions. The inside of a beam chamber is brighter than the surface of the Sun, and the light vaporizes or outgases impurities on the walls of the vacuum chamber, which interfere with the beam. The cure for outgassing was to shine synchrotron light on the chamber walls to liberate the impurities (a process known as “scrubbing”) and

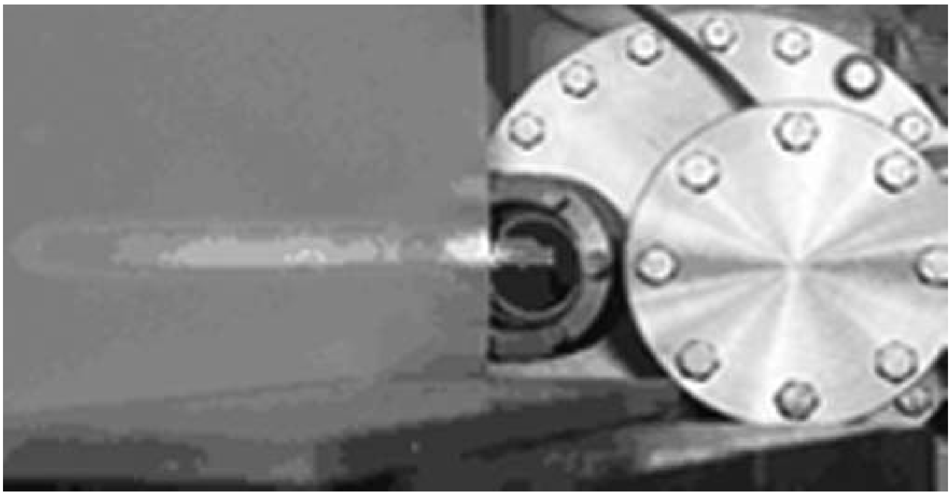

Fig. 5. The visible light emerging from port 14 of the UV ring in May 1982. *Credit*: Brookhaven National Laboratory.

then to pump the impurities away – which was a Catch-22: you needed beam to scrub, but a scrubbed chamber to get beam. "We commissioned that ring by brute force," said Blumberg. "We bootstrapped our way by getting a little beam, outgassing, getting a little more beam, outgassing some more, and so forth." This would turn out to be a classic problem in commissioning synchrotron-radiation sources, affecting not only the NSLS and the Aladdin synchrotron-radiation source being built at the University of Wisconsin, but most other sources.

By February 1982, the UV ring was still running at only 20 mA (milliamperes); design current was about 1,000 mA. In March, the machine was shut down for a month of repairs and for installation of an insertion device. When the UV ring came back on, it reached 40-50 mA with lifetimes of 20 minutes. In the ensuing months, the ring slowly achieved higher currents and longer lifetimes. Some ports were opened for first time and visible light was seen in windows. In May 1982, visible light emerged from UV port 14 (figure 5). But the light was not centered on the beam ports, and throughout June and July corrections were made to align the beam lines.

The final day of September 1982 was nominally the end of the four-year construction period. The machine still needed much more work. The UV ring was running at 80 mA and at 600 MeV, with a lifetime of about half an hour, far too short for serious experimentation. The beam lifetime in a UV ring is limited by intrabeam scattering – the Touschek effect – which is strongly energy dependent, and would be greatly ameliorated once the energy of the UV ring could be increased to 750 MeV.

Five beam lines began experimentation. Although it was the brightest UV source in the world, it was nowhere near its design specification of 1,000 mA. The UV jalopy was lurching along too slowly to be of service. At least it was moving.

X-Ray Ring

The same could not be said of the X-ray ring. It, too, had experienced harmful budget compromises. Its design called for six vacuum ports per superperiod but only four pumps per superperiod were installed. The rf cavities were delayed by budget shortfalls; when they finally arrived, they proved too difficult to weld and a new set was ordered from a different manufacturer – and even those proved faulty and had to be rebuilt at Brookhaven. The rf amplifiers had to be ordered without control circuitry, which the NSLS engineers had to install themselves. Electrodes for clearing – eliminating ions from the chamber – and baking out – raising the temperature of the chamber to remove impurities from the walls – were not installed (some small clearing electrodes were placed inside the vacuum pumps, but since the main source of outgassed ions was the inside of the bending magnet, this was inadequate). Beam instrumentation was almost laughingly nonexistent, and during the beam commissioning the scientists were almost completely dependent on the by-then antiquated method of viewing fluorescent screens and eyeballing. On top of everything else missing at the X-ray ring, it had lost Hsieh, its chief engineer.

Then a development at ISABELLE brought Hsieh back.

In June 1981, thanks to Robert Palmer, the ISABELLE project found its technological fix, in the form of a new design that replaced the troublesome braid with a cable, while keeping the same basic structure and tooling of the magnets. In September the braid project was shut down, Palmer was made head of the Magnet Division, and all effort was devoted to the new magnet in a desperate attempt to get the community and the DOE behind ISABELLE again. Hsieh, knowing Palmer was already working on the cable with Brookhaven's most eminent engineer, Ralph Shutt, asked to be released. Palmer agreed, and a delighted Hsieh returned to his baby. But the baby's condition had not improved much since Hsieh's departure the year before. Owing to continuing delays from budget cuts, short staffing, and redirection of lab resources to ISABELLE, the ring was still incomplete.

Formation of Participating Research Teams

Like everything else about the NSLS, preparation of its usage had created fresh kinds of problems. These were being handled by Martin Blume (figure 6), who became head of the Synchrotron Radiation Scientific Program after van Steenbergen had been selected as the NSLS project head.

The NSLS was a facility that was large enough to fit the pattern in which the government assumed responsibility for a "Big-Science" facility such as an accelerator or reactor. But the NSLS was unlike accelerators or reactors in that the work performed at it would be essentially "small science." The vision was that the NSLS would be more like an electrical-power plant than an accelerator or reactor, in that the facility would deliver synchrotron radiation as a commodity for a wide range of interdisciplinary applications. To use electricity, one needs to build an electrical-power plant and have an easy way to hook it up to users. But users of electricity are diverse, and the best people to cook up new ways of using it and experiments to perform with it would be very

Fig. 6. Martin Blume, Head of the Synchrotron Radiation Scientific Program. *Credit*: Brookhaven National Laboratory.

different from those who build and operate power plants. The builders of the NSLS and the Stanford Synchrotron Radiation Laboratory (SSRL) were especially interested in encouraging a wide range of industrial users to collaborate with academic and laboratory users of the machine, to free them if possible from the supervision of laboratory-program committees.

At the NSLS, two kinds of mechanisms were devised to handle users. One was a conventional user group of the sort already common at accelerators and reactors. So-called "facility beam lines" would serve such general users, whose front ends would be built by NSLS scientists. Time would be allotted by a standard Program Advisory Committee. In a second and novel kind of mechanism, the front end would be designed and instrumented by a team of outside users. In exchange, this team would be given priority for a fraction of the scheduled beam time for a specific period, while the rest of the time would be allotted to general users by the Program Advisory Committee. In devising a name for such a group, van Steenbergen vetoed ones that would result in voweled acronyms like CUGs, CAGs, and CATS; this last one, which stood for Collaborative Access Teams, had the additional disadvantage that wags coupled it with the contrasting DOGs, for Disgruntled Outside Groups. Van Steenbergen insisted on calling them Participating Research Teams, or PRTs.

PRTs seemed a good way of ensuring the flexibility and originality of small science at the facility. "In this way intervention by the Program Advisory Committee would be kept to a minimum and a 'small science' atmosphere would be maintained."[8] They were also an excellent way of getting outside money for construction of experimental facilities at a machine that was already short of funds.

PRTs were mentioned already in the first announcement seeking expressions of interest or intent, in September 1978. A few months later, the laboratory hosted a users' meeting to foster the formation of PRTs that attracted some 200 people and resulted in the formation of a dozen groups, including ones from Bell Labs, IBM, and the University of Pennsylvania.

A problem was created, however, by the propriety of the participation of industrial users at a laboratory that had been built from public funds. This problem had already arisen at the SSRL, which had attracted industrial users since its beginning – Xerox Corporation, for instance, whose scientists had built a monochrometer for its beam whose design eventually became standard at synchrotron sources. The SSRL's expansion – it began with one beam line and grew to eleven – forced it to clarify the status of its industrial users with its funding agency, the National Science Foundation (NSF), and with its home institution, Stanford University. This proved to be problematic. When SSRL Director Arthur Bienenstock first approached the NSF in the mid-1970s, he found them receptive in principle to industrial participation. But the NSF was under pressure from the American Council of Independent Laboratories, which had an ongoing complaint about unfair competition from various university researchers using federally-funded and tax-free services. The SSRL's expansion inspired the NSF to reexamine its policies regarding the funding of facilities with industrial participation: The eventual outcome was "Important Notice 91," a NSF policy paper that walked a careful line between encouraging "unique facilities" with industrial-collaboration potential such as the SSRL, and avoiding competition with industry.[9] Stanford's attitude was more of a hurdle, for the university forbade proprietary research on campus. The university would, however, allow a one-year delay (later shortened to 90 days) in the publication of research for patenting purposes, and SSRL and Stanford officials came to an agreement over work to be done at the SSRL consistent with this regulation.

The DOE, which funded the NSLS, had another obstacle to industrial use. The principal one was DOE Order No. 2110, which dictated that outside users of DOE facilities pay "full cost recovery" – not only their operating costs, but an additional sum covering part of their construction.[10] A single exception to this rule was permitted to allow university scientists to work on approved high-energy physics projects at high-energy physics laboratories.

In practice, industrial users had been performing basic research at DOE-funded national laboratories for years without having to pay full-cost recovery. The laboratories had effectively circumvented the rule by declaring that such users were collaborators. That ruse would not work, however, for something on the scale of the NSLS and of other second-generation synchrotron-radiation sources – huge, single facilities with a hundred or so beam lines to be funded by the DOE and made available to multiple users. Full-cost recovery would be approximately $300,000 per year for a beam line. Apportioning full-cost recovery fairly among ever-changing groups would have been extremely difficult; Blume complained sarcastically that he would have to install coin-operated shutters on the beam ports to cut off the photons when the money ran out, like those on binoculars at tourist traps. Moreover, the cost would have discouraged precisely those people the NSLS planners most wanted to involve. "Full cost recovery might not have bothered the usual suspects – IBM and AT&T," Blume said. "But it would have made even the richest of the other industrial organizations pause, and university people would have been blown out of [the] water; entire NSF grants would have gone to pay for the light source. We clearly had to get the policy changed."[11]

That proved to be a struggle. Standing in the way was a firmly entrenched attitude, shared by DOE officials and university and laboratory scientists, that opposed collaborations between national laboratories and industries. DOE officials were reluctant to give anything away that might wind up in the pockets of industry, while university and laboratory scientists resented that while they had course loads and committee work, industry scientists had no such burdens and would essentially be getting beam time for free. Blume and other partisans, including Bienenstock, worked to convince both groups to cooperate through the summer and fall of 1978. Whenever Blume was called to attend a meeting on basic-research policy and asked what he wanted on the agenda, he would say, "industrial participation in basic research facilities and single-source funding for multi-purpose facilities." Colleagues began kidding him that the phrase was his version of Cato's *Delenda est Carthago* ("Carthage must be destroyed," the famous line with which the orator and politician Cato the Elder ended his speeches in the Roman Senate against the city's rival.

In March Blume convinced Vineyard to send Jim Kane of the DOE a letter pleading for a change in DOE policy for charging for beams at the NSLS. "Bell Labs has already budgeted $780,000 for instruments, and it is possible that they will withdraw the offer if they are requested to add the annual operating costs [$300,000 per beam line for full-cost recovery] to their budget."[12] Then, in June, Blume testified before a subcommittee of the U.S. House Science and Technology Committee, where he pleaded for parity between academic and industrial usage of the NSLS, pointing out that the Japanese government made its synchrotron-radiation facility available to industry.[13] Blume asked Hank Grahn, BNL's Assistant Director for Financial Planning, to write a letter of complaint to the manager of the DOE's area office about DOE Order No. 2110. Quoting the passage of DOE Order No. 2110 about full-cost recovery, Grahn wrote that "this section … will lead to serious problems!" Grahn added. "It is particularly important to encourage industry to increase its commitment to basic research. … Proprietary utilization should not be allowed to interfere unduly with the basic research program."[14]

Finally, in 1979, the NSLS advocates prevailed and the DOE issued the following guidelines:

> If the research to be done is of documented programmatic interest to the DOE, and if the user agrees to publish the results of the research in the scientific or technical literature, there will be no charge for the use of the facility. This will be the procedure irrespective of the origin of the user – national laboratory, other government agency, university or industry.... If a user wishes to use a designated BES [Basic Energy Sciences] facility for proprietary purposes, a fee that realizes full cost recovery must be charged.[15]

The DOE insisted on reserving for itself the rights to any patents that were granted based upon the work.

At a meeting two months later, Blume pressed Kane for an interpretation of "programmatic interest," and was told that "this was meant to be broadly interpreted and that the determination would be left to the facility managers."[16] Blume also sought, and eventually succeeded in obtaining, a blanket patent waiver from the DOE for patents obtained through proprietary research at the NSLS, further encouraging industrial participation.[17]

Meanwhile, the NSLS project chugged along officially. At the third annual NSLS Users Association meeting in June 1981, van Steenbergen cheerily announced that the UV ring would begin operation in September, the X-ray ring in December. In October 1981, the NSLS Project became the National Synchrotron Light Source Division – a year later, it became a Department – whose head was John McTague.

McTague's Ph.D. degree was in physical chemistry from Brown University; he had worked at the North American Rockwell Sciences Center in Thousand Oaks, California, and then had been a Professor of Chemistry at the University of California at Los Angeles (UCLA), before becoming the first Director of the NSLS. He was about to find the transition to become head of the NSLS difficult. He was expecting to take over a facility that was on the verge of supporting a large and diverse experimental program. Little in his training had equipped him to solve the kind of problems that were preventing the facility from operating. The best he could do was to focus on the NSLS's eventual scientific program, and on its eventual renovation, involving additional building space and equipment, now being called "Phase II."

On the X-ray ring, no beam was achieved through the first half of 1982 – despite what was billed, in May 1982, as the "last General Users meeting before full operation." Nevertheless, the laboratory administration remained upbeat. "NSLS seems to be progressing steadily," McTague wrote Vineyard in June, "The x-ray floor is beginning to look like a real science lab!"[18]

Looks deceived. Almost nothing was progressing. Or, rather, nothing on the machine was progressing, though the experimenters were installing their equipment. The poor quality of the hardware was one culprit. Another was that the NSLS builders were discovering the toll that high brightness was placing on the machine. This, too, was partly because the NSLS was the first facility of its kind. While high-energy physicists were accustomed to the notion that you always need bigger machines, and have to do Research and Development (R & D) on bigger machines, condensed-matter physicists were not used to this – they wanted something like an electrical-power plant.

In a high-brightness accelerator, an extremely narrow, high-energy beam is threaded through a warren of complicated lenses. This beam must be kept to a small volume and a small angular divergence. To keep it that way requires, among other things: (1) placing the magnets with extreme precision, so that the beam comes through correctly; (2) extremely uniform power supplies, since any rippling in the power supplies causes the beam to ripple; and (3) an extremely high vacuum.

In the first half of 1982, the NSLS builders had begun to encounter the first of these requirements. A high-brightness machine requires a much finer precision in magnet placement than accelerator builders at Brookhaven were accustomed to. While one survey had already been done, Krinsky – the nominal coordinator of the X-ray ring commissioning, and one of those talented youngsters who often chafed under van Steenbergen's tight rein – suspected that the survey had been insufficiently precise, and felt that higher precision was necessary. A high-precision survey was expensive – on the order of $25,000 – given the shoestring budget, and would have meant shutting down the ring for about six to eight weeks. In yet another money-saving move, van Steenbergen gambled that he could do without a survey of the magnet placement. Krinsky, a former high-energy theorist with a deep analytical sense, disagreed, and argued that high-precision alignment was essential to achieve a stored beam.

This was an exemplary case of the clashes that occurred frequently during the machine's commissioning. Van Steenbergen's pragmatic and empirical approach was to push the commissioning fast, to turn things on at the earliest opportunity, to see what was wrong and fix things as they came up. He wanted to learn about problems in series. This had been the accelerator-construction style at Berkeley in the early days, when Ernest Lawrence and his crew built things by the seat of their pants. Krinsky's analytical approach was to shut the machine down and make a thorough and orderly analysis of it. He wanted to learn about the problems in parallel before prioritizing and rebuilding. This had been Brookhaven's approach with the Cosmotron, and had been passed along to him through Renata Chasman and Kenneth Green.

The conflict over the survey lasted through the first half of 1982. In July, van Steenbergen left on a trip to the Far East. Blume, with a dawning appreciation for the difficulty the machine was in, authorized Hsieh to conduct a resurvey. Shortly after it was completed, on Saturday, September 4, 1982, a long-duration beam appeared in the X-ray ring for the first time, though at very low current and without acceleration.

Thus, at the tail end of the four-year construction period, both the UV ring and the X-ray ring had beam. Van Steenbergen had done the impossible. He had built the handyman car on schedule and on budget.* It was not performing anywhere near as well as planned and was not able to support an experimental program, and its users

* The NSLS came in at $24 million as budgeted: $1.0893 million for the injection system, $4.7541 million for the X-ray storage ring; $1.9453 million for the UV storage ring; $3.2736 million for associated equipment; $1.6147 million for experimental equipment, $3.888 million for engineering, design, and inspection; and $7.435 million for the general construction.

were screaming that, as a result, their research programs and careers were being damaged. But it was there.

Dedication

Meanwhile, prospects for ISABELLE remained bleak. Though the technical fix had been found, it was too late. A group of scientists at Fermilab were building momentum for an effort to cancel ISABELLE and build instead what was being called a "Superconducting Supercollider." BNL Director George Vineyard had been ousted, and Nicholas Samios was Acting Director.

The Brookhaven laboratory administration seized on the good piece of news to plan a dedication for the NSLS. The event took place on November 22, 1982 (figures 7 and 8). Lab Director Samios was the master of ceremonies, and speakers included McTague, Don Stevens, the local Congressman William Carney, and George A. Keyworth, President Reagan's science advisor. Samios announced that the NSLS Division was being upgraded to a Department. Stevens recounted the history behind the interest in synchrotron radiation. Carney noted the national attention that the facility would bring to the region. McTague predicted that within a year fifty experiments in a wide variety of fields would be running at the NSLS. And Keyworth declared that the machine meshed well with the young administration's interest in federally-funded R&D projects of relevance and quality.

For a third time, the fanfare did not impress those closest to the machine. "It was hard to get euphoric, knowing what still lay ahead," recalled Galayda. At the ceremony, van Steenbergen mentioned to Hsieh a comment he had once heard Fermilab's Robert R. Wilson make, to the effect that if an accelerator is easy to commission, it's been way overdesigned. "That guy builds machines," Hsieh remembers thinking, wryly. Furthermore, Morris Perlman, another early promoter of the machine, had passed away. And having lost his long-time collaborator, Richard Watson lost his desire to invest more energy in the machine, and decided to return to his laboratory.

With construction funds exhausted, funding now became an even greater problem. In many new machine projects, the project heads can pillage the operating funds of the machine that preceded it; Samios, in fact, had tried to raid AGS operating funds for ISABELLE. But the NSLS was the first machine of its kind at Brookhaven. Blume scrounged for money around the lab, raiding capital equipment budgets and anything else he could. Then came a small windfall. Earlier that year, Blume won the prestigious Lawrence Award, the first materials scientist to do so. He used his new influence to convince the DOE to contribute $50,000 to the NSLS. McTague, meanwhile, was good friends with Keyworth, and used his influence with the Presidential Science Advisor to promote Phase II.

But for the moment van Steenbergen's pragmatic approach was left in place. In December 1982, X rays came out of a beam port, X-13, for the first time, and the next month were streaming down the beam line. But little improvement was made through the spring of 1983. The X-ray ring remained touchy, the engineers could not raise the current much past 0.25 mA, and far less radiation was coming out of the ring than required.

Fig. 7. Invitation to the dedication of the NSLS on Monday, November 22, 1982. *Credit*: Brookhaven National Laboratory.

Further Delays

Normally, experimentation follows dedication, perhaps prefaced with some trouble-shooting. But the NSLS, built on the cheap with numerous cut corners, still needed a lot of work. The effects of the budget compromises now surfaced, and each time one problem was solved a new one cropped up. One now did, having to do with the power supplies. When the power-supply regulation is not right, what is supposed to be a narrow thread of a beam broadens. The electron beam fluctuates, and the acceleration system is not reproducible. Another gamble van Steenbergen had taken was to utilize power supplies from decommissioned synchrotrons – the CEA and the Princeton-Penn

Fig. 8. The dedication ceremony of the NSLS on Monday, November 22, 1982. At the podium is George A. Keyworth, and seated (left to right) are Nicholas Samios, John McTague, Don Stevens, and William Carney. *Credit*: Brookhaven National Laboratory.

Accelerator – and to accept their calibrations at face value. But the tolerances for a storage ring were stricter than for a synchrotron, and for a synchrotron-radiation source had to be much stricter still. After extensive study, Krinsky concluded that the quadrupole power current was not constant but rippling with time, and as a result the focusing of the magnets also was fluctuating. He asked van Steenbergen to take new measurements with state-of-the-art equipment, but the latter refused for months, because this would mean having to turn off the machine for a few days and redirecting some valuable resources. Eventually Krinsky prevailed, and careful measurements confirmed that the power current was indeed varying. While the NSLS had been built for a tolerance of one part in ten thousand, the current was varying by one part in a hundred. The effects on the beam orbit were large and time varying, and resulted in an unreproducible system. "We paid a huge price for those power supplies," Hsieh said. The ring had to be shut down for two months to rebuild the power supplies.

Users were now complaining. They had trouble enough adjusting to the scale of the machine – it was a qualitative leap in scale for them, too. People used to working with pry bars and nuts and bolts to position optical and experimental apparatus suddenly were confronted with the need for an order of magnitude or more finer tuning for the whole system. And now the machine was two years behind schedule. Faculty from the U.S. and abroad who had arranged sabbaticals to work on the NSLS found they had lost the time, graduate-student research was held up, and many scientists felt that not only their research but their careers were in jeopardy; "You don't get tenure for building beams, but for getting results," one told me. Users protested that they were having to put themselves in a state of "suspended animation."

Meanwhile, other synchrotron-radiation sources were cropping up all over, providing competition for the Brookhaven machine. During this same period, the University of Wisconsin Synchrotron Radiation Center built a new 1-GeV (giga-electron-volt) storage ring named Aladdin, which replaced the old Tantalus I (part of which was later sent to the Smithsonian Institution in Washington, D.C., for eventual exhibit). Aladdin, too, would have severe commissioning problems, over some issues similar to those at the NSLS. In Japan, the Photon Factory was completed in 1982 at the High Energy Accelerator Research Organization (KEK) in Tsukuba. In Berlin, a 0.8-GeV storage-ring facility, the Berlin Electron Storage Ring Organization for Synchrotron Radiation (BESSY), began serving users in 1982. And in Orsay, France, LURE (*Laboratoire pour l'Utilisation du Rayonnement Electromagnétique*) began operating an 800-MeV storage ring, SuperACO, in 1984.

McTague found himself more and more on the defensive in front of NSLS users. At the NSLS users' meeting in June 1983, he spoke optimistically about Phase II with its promise of improved brightness, better insertion devices, and expanded facilities. This provoked numerous annoyed responses from experimenters, including Cully Sparks of Oak Ridge, the chair of the Users' Group and a former NSLS promoter, who raised the issue of "radiation now versus insertion devices later." Sparks bluntly asked:

> [W]hen is stabilized beam and anticipated brightness going to be achieved in the VUV [Vacuum Ultraviolet] ring, and when is the x-ray ring going to produce? These questions are so strongly felt among the User community that discussions and issues raised which do not center on accomplishing improved performance from the bending magnet lattice appear only to cloud the real issue.… Any allocation of resources to other tasks, such as Phase II, appears as a distraction from what should be your main responsibility to those Users who have invested in bending magnet beam lines.… [T]he users are not going to be placated by promises of a factor of three or more improvement from insertion devices.[19]

To add insult to injury, the cover story of the June 1983 issue of *Physics Today*, entitled "Synchrotron-radiation research – an overview,"[20] contained no mention of the NSLS. Written by Arthur Bienenstock and Herman Winick of SLAC, and heavily promoting that lab, it was accompanied by no photographs of any lab but SLAC. It even managed to call attention to the low-emittance concept in one sentence without mentioning the NSLS. Now it was Brookhaven's turn to complain angrily that SLAC was leaving their lab out of the loop.

When the X-ray ring was turned on again at the end of June 1983, after the shutdown to rebuild the power supplies, the current increased, but only to a few mA.

Blume was now determined to intervene. As an administrator, he had few means of judging the right way to step in. Whom to trust – how, indeed, could he go about trying to find the right person to trust?[21] In midsummer 1983 he had an opportunity of sorts. That opportunity came from a disaster for the lab – the cancellation of ISABELLE (renamed the Colliding Beam Accelerator, or CBA, in a fruitless attempt to rekindle enthusiasm). The cancellation liberated the attention of many of the lab's accelerator builders, and a few of the lab's resources. Blume invited two people to come look at the NSLS, one from inside the lab and one from outside.

The insider was Mark Barton, the head of the Accelerator Department who had helped bring Chasman and Green into the NSLS project, and who now was head of a Task Force to look into making a Heavy Ion Facility out of the remains of CBA. "You need more help," Barton said, providing a candid assessment of the problem.

> You have an enormous task ahead to bring that ring close to design performance. There should be more physicists working on these problems; more support from engineers, programmers, and technicians; and more support from Laboratory management to get faster turn-around in the shops.… The lack of physicists showed in the discussions of instrumentation, correlation of measurement with theoretical results (lack of theoretical predictions in some instances) and the fact that it was necessary to pull teams away from the X-Ray Ring work to bail out VUV Ring crises. The need for more technical support is obvious in the fact that you seem to have everyone busy fixing things with so little margin for attacking independent new approaches to major problems.… I urge you to use every means at your disposal to pressure management to provide you with additional help. The Laboratory must recognize that failure to bring this storage ring to a respectable level of performance in an orderly fashion could be a major embarrassment which cannot be afforded at this time.… Most important of all; do not get discouraged or let anyone push you to panic. Your program will get the ring operating with excellent performance parameters. Additional support would help you get there sooner.[22]

The other person was Ewan Paterson, the experienced hand who had been one of Brookhaven's first choices for a project head. Blume was hoping not only to tap his advice but possibly also to persuade him to come and take charge of the NSLS Department.

> [I] was immediately aware of the many conflicts between running the VUV ring for physics and the X-ray ring for machine development.… I also observed the usual conflicts between beam on time development versus engineering development which are standard in developing a new machine.… Overall I saw nothing at the X-ray ring that could not be explained by current "engineering" limitations that will be removed in time.[23]

The advice of these two was valuable, for it gave Blume confidence that it was possible to rescue the NSLS. Still, with van Steenbergen in charge, the pragmatic approach continued, and the machine's problems lingered into the fall. At the beginning of October the maximum current of the X-ray ring had only increased to about 15 mA. The absence of the anticipated radiation in the beam lines was found to be due to a misplacement of the vacuum chambers in the dipole magnets, sometimes by as much as a centimeter.

The UV ring, meanwhile, was supporting some modest experimentation. Its builders were still struggling to increase the beam lifetime. One challenge was to improve the vacuum. Another was coping with the Touschek effect, that electrons in the same bunch tend to scatter off each other, which turns out to be the dominant factor affecting the lifetime of a UV beam. The UV's modest success was now detrimental to the X-ray ring because it was tempting to devote resources to something exhibiting positive results, even if only incrementally.

The next major problem related to brightness that surfaced had to do with the quality of the vacuum. A good-quality vacuum, it turned out, is essential for supporting a high-brightness beam. The vacuum inside the X-ray ring was not good enough, and had to be treated carefully. "Getting a high quality vacuum is like winemaking," Krinsky said. "There's whole series of steps you have to do right. You don't understand every step, but if you follow the recipe you get a good vacuum. Someone will say, 'you don't need that step,' and sometimes its right and sometimes it's not. You have to be careful. And we hadn't had much experience at Brookhaven with ultrahigh vacuum."

One common step to achieve a good vacuum is a "bakeout," a standard cleaning operation in which the vacuum system is heated to expel impurities from the walls. Electrical tape is wrapped around the vacuum chamber, then covered with aluminum foil. Heating elements inside the chamber are turned on to raise the temperature as high as possible without damaging any of the seals, to about 150o C. From the outside, nothing visible is happening, though one's nose easily detects that a bakeout is in process, for the entire room smells like a hot toaster.

The X-ray ring was baked out at the end of 1983, but the result was still only an incremental improvement. Then, mysteriously, the beam began to vanish entirely. This turned out to be due to yet another unexpected problem. When the vacuum was imperfect, there were some ionized atoms inside the chamber, giving rise to a cloud of positively charged ions that would eventually blow up the beam. It turned out that this blowing up of the beam had masked instabilities in the beam. So when the vacuum was finally cleaned up and the beam squeezed down, the instabilities blew up the beam – and it vanished. Krinsky and Claudio Pelligrini went to work analyzing these newly discovered instabilities.

Change in Approach

As the end of the year drew near, the users were still clamoring and little progress was in evidence. The rf system did not work right, the vacuum was a mess, the power supplies still could not regulate the current in the magnets properly, and the injection was a shambles. In principle, it should have been possible to run the injector only two minutes for each fill. In practice, the injection system was so unreliable that the scientists did not dare shut it off because it would take too long to get it running again, so they left it running all of the time.

"None of the hardware engineering was up to the standards to make an accelerator work," recalled Krinsky, "throughout the *whole* synchrotron light source, starting with the injector, the linac, the booster ring, the controls – then on to the UV ring, the rf system, the vacuum, the magnets – you name it, none of the parameters were rock solid, where you could turn it on and have confidence that you had the machine set where you wanted it." The builders and users were now paying the price for a machine of cut corners.

Most ominously of all, the perilous situation had attracted the DOE's attention. The agency, "concerned about the delay in bringing the X-ray ring up to operational level," announced its intention to review the project. The DOE felt a special urgency given that it was about to fund the Phase II construction project – at $19.7 million to be spent over three years, about the same scale as for building the machine itself – without its Phase I in order.[24] Blume and others feared that the DOE might back away from the NSLS as it had from the recently-cancelled ISABELLE. If the DOE could cancel that big project, one whose technical problems had been fixed, it could cancel anything. It was indeed a perilous situation – a nonworking machine, a management unable to fix it, and a looming DOE review – for the NSLS and for Brookhakven.

In November 1983, heads began to roll. Blume stepped in as Acting Chairman of the NSLS, replacing McTague. He began raiding individuals from wherever he could to help out on the NSLS; jokes circulated around the lab about "Blume's pluckings," and with ISABELLE's recent demise there was quality fruit about. Blume appointed Barton as Deputy Chairman, replacing van Steenbergen; the two new department leaders became known as $(MB)^2$. This transition was risky. Blume was not an expert on accelerators, Barton had been working at the NSLS only part time for a few months, while the person he had replaced, van Steenbergen, had headed the NSLS project for six-and-a-half years.[25] Finally, Blume put Krinsky in full control of the X-ray commissioning. This, too, was a risk. But several factors gave Blume confidence. One was Barton's and Paterson's earlier analyses. Another was Krinsky's record in arguing for the survey and in uncovering flaws such as those in the power supplies. A final factor was that Krinsky's systematic and analytical approach resonated with Blume's own, extending the tradition that Chasman and Green had brought to the project in its early days.

Blume convinced the DOE to hold off its review until May, leaving him only six months to put the machine in order. He halted van Steenbergen's pragmatic approach to the machine commissioning and began a critical analysis of the accelerator's systems. He ordered a shutdown of the machine, divided it into subsystems, and charged different groups with analyzing each subsystem, aiming to turn the machine back on in April. He brought in outsiders to help out with each subgroup, and provided additional funds. He gave the machine builders another achievable goal for the April turn-on – 50 milliamps at 2 hours lifetime by the time of the DOE review. Blume knew this was doable: it had once been done. It would be an achievement to do it regularly, and while it would not be good enough to run experiments, it would be good enough for a thorough scrubbing.

The Linac was worked over and the Booster got new kickers. The transfer lines got separate power supplies, and power supplies elsewhere were rebuilt. On the X-ray ring, the rf system was improved and two new cavities were built and readied for installation. The diagnostics and controls were overhauled. An international workshop was held to review the design and performance of the vacuum system, and its final recommendations were implemented by a task force under Henry Halama, a "pluckee" formerly with the ISABELLE project.[26] Halama added new pumps, replaced poor-quality parts, cleaned and reinstalled others, and often took pieces of the chamber apart several times before he was satisfied. Thanks to the new funding and extended schedule, Halama was able to conduct a more thorough bakeout than ever before, and was careful to condition the distributed ion pumps during bakeout. By April the vacuum was at 10^{-10} torr, an order of magnitude better than earlier.

The machine, shut down in February, was turned back on in April. Blume's goal was met. The UV ring soon began performing reliably, running at 750 MeV (above the design energy of 700 MeV) and at 400 mA (below the design current of 1,000 mA). The X-ray ring reached 40 mA after a few days, and soon reached 80 mA at 1.7 GeV, and 50 mA at 2 GeV, though this was still far below the design parameters of 500 mA at 2.5 GeV.

The DOE review began at the end of May.[27] To everyone's relief, it was optimistic. "[W]hile the NSLS has experienced long commissioning delays," the final report stated, "the delays do not result from fundamental technical problems that will prevent the facility from fulfilling its promise, but rather from economic and management issues." It anticipated, by the end of 1984, that the X-ray ring would be operating at 50 mA at 2.5 GeV, with a two-hour lifetime and with six working user lines. This would "constitute a viable operational base from which useful research could proceed while the substantial remaining machine commissioning and further user-access commissioning is completed." But while "very substantial progress has been made in the last six months, morale is good, and the progress should continue," the report pointed out, much remains to be done and the project needs additional "key accelerator physics and engineering staff and support" over the next two years. The report also recommended another technical review in 1985, and a followup workshop on the commissioning experience.

What had gone wrong? The report mentioned several factors. One was a set of design decisions about tradeoffs and recycled parts that, while making "the project more palatable to the funding agencies and the community," also increased "the difficulty, time required, and cost of bringing the facility into full operation." Examples included the omission of glow-discharge clearing electrodes in the vacuum chambers, whose cost "would have been small compared to the cost to provide this capability now." Another factor was the attempt to commission "two separate, state-of-the-art rings into operation simultaneously with available resources." Yet another was the impact of the CBA, which had consumed accelerator resources and lab attention until the previous year.

Over the next year, as Phase II began to get going, the NSLS exhibited obvious improvement. Blume called Heese – the one person who thoroughly understood the Booster – in Canada and prevailed upon him to return to the NSLS. Under Heese's guidance a new injector was installed. Two new rf cavities were built and installed. In April 1985, NSLS got its first permanent director, Michael Knotek. The following month, after extensive renovations, the first operations began. Later, the Linac would receive a new electron gun; a third accelerating section, modulator, and klystron; and the existing modulators were rebuilt.

The state of suspended animation came to an end (figure 9). In fact, it ended abruptly, thanks in part to Heese's refurbishing of the injection system. The state of suspended animation ended so quickly that it took many experimenters who were anticipating

Fig. 9. The NSLS building as seen in 1982. *Credit*: Brookhaven National Laboratory.

more time to phase in their work by surprise. *Science* magazine devoted a long article to what it headlined as the end of the "X-ray drought" at the NSLS.[28] And in August 1985, Heese was determined to get the machine up to its design energy of 2.5 GeV by hook or crook. One Saturday he and a Norwegian engineer named Rolf Olsen roamed the laboratory looking for a transformer they could use to augment the output voltage of the X-ray dipole supply, stole one from a laboratory, spent Sunday peeling off some windings and making it suitable, and installed it. The next day – Monday, August 19, 1985, at 6 PM – the X-ray ring at the NSLS first met its design energy of 2.5 GeV.

That October, the NSLS had its promised followup workshop on its construction experience, comparison with the experiences of other synchrotron sources, and implications for the future (BNL 51959). Participants came from most of the major dedicated synchrotron facilities around the world. Blume and Galayda opened the workshop by reviewing mistakes that had been made during the NSLS construction:

> Many compromises in the design were made, and second-hand equipment was used in the construction in an effort to save money. In the end, these efforts came at considerable cost, both financially and in strain on the staff. It is fair to say that such

> steps should be rigorously avoided in the future, but it is equally fair to say that our community will undoubtedly do it again. When faced with a choice of inadequate funding or no funding at all, we will probably choose inadequately [funding].

Many problems remained that could not be eliminated by repairs and upgrades. One was the sensitivity of the Booster. For years it would be so touchy that when it did not work the only time-honored remedy was: "Call Heese."

Conclusion

The NSLS story is an important element in the story of how synchrotron radiation made the transition from a new phenomenon to a commodity, and how synchrotron-radiation researchers made the transition from pirates to establishment. The NSLS story illustrates, as well, many of the tensions and risks involved in building a large scientific facility in the modern, highly politicized environment: risking the facility's quality by underfunding it *versus* asking for more funding and risking not getting it; focusing on meeting time and budget promises that risk compromising machine performance versus focusing on performance and risking cancellation; and the pros and cons of a pragmatic versus an analytic approach to commissioning.

As a negative example, the NSLS story illustrates the need to choose carefully the compromises that one makes when building an underfunded machine. No one could have built the NSLS and met its design tolerances and specifications for $24 million. But progress could have been made with less trauma, and with better performance earlier for users. If one knows that a facility is not going to come in on time and on budget, decisions can be made regarding what to leave for later so that the project can be upgraded as smoothly and effectively as possible. That requires experience, and a special kind of leader: the Wilsonian model requires a Wilsonian character. Unlike Robert R. Wilson, Arie van Steenbergen did not try forcefully and regularly to stretch the limits that had been imposed upon him. He might have seen the double-digit inflation at the time as an opportunity instead of a constraint, for instance, and pressed BNL Director George Vineyard more forcefully to lodge with the DOE the legitimate complaint that inflation had not been factored into the NSLS budget and thus it ought to be augmented. But Vineyard, for his part, might have been more receptive to the validity of van Steenbergen's occasional complaints about the machine's budget.

As a positive example, the NSLS story illustrates the extent to which success or failure in navigating such tensions depends upon the resources of the institution building it. The times when the NSLS project almost collapsed were times when it was starved for resources; its eventual success depended upon the depth of accelerator talent, management talent, engineering talent, and scientific talent that happened to be at Brookhaven – it depended upon Blume as a concerned manager, upon everything and everyone he was able to pluck, and upon the resources that he was able to redirect. That in turn depended upon Brookhaven's interdisciplinary depth. His rescue of the NSLS was a function of the range and quality of resources that the laboratory eventually was able to devote to it – that, and the severity of its problems, which riveted the attention of the laboratory. As Blume said, "nothing sharpens the mind like a death sentence."

The NSLS had an immediate impact on Brookhaven's research by cementing its strength in solid-state physics, fostering new kinds of interdisciplinary research, and creating new kinds of interactions among laboratory, university, and industrial researchers. Its success in the middle-to-late 1980s also helped Brookhaven to survive as a laboratory during the period following the termination of ISABELLE in 1983, prior to the construction and use of the Relativistic Heavy Ion Collider (RHIC). "The light source was a lifeboat during that period," said Blume. "It was to Brookhaven what the lunar module was to Apollo 13." In the still-longer run, the NSLS also would be a key element in the laboratory's transition from high-energy physics to basic-energy science. And it would also foster new techniques and fields.

A final irony of the NSLS story is that this facility, an order of magnitude smaller in scale than ISABELLE – the collider whose fate was thought to be tied to that of the lab – transformed not only Brookhaven's culture and identity far more profoundly than that high-energy accelerator could or would have, but also the lab's prospects. For within a quarter-century following the completion of the NSLS, governmental priorities had changed markedly. While high-energy physics struggled to stay alive, basic-energy sciences (including materials science) of the sort served by the NSLS began to experience rapid growth. This helped make it possible for the NSLS, which was the premier synchrotron-radiation source in the world through the 1990s, to remain a leading source even after the construction of other, next-generation sources.

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