SUPERBEND UPGRADE AT THE ADVANCED LIGHT SOURCE*

D. Robin† for the Superbend team, LBNL, Berkeley, CA, USA 94720

Abstract

At the ALS there had been an increasing demand for additional high brightness hard x-ray beamlines in the 7 to 40 keV range. In response to that demand, the ALS storage ring was modified in August 2001. Three 1.3 tesla normal conducting bending magnets were removed and replaced with three 5 Tesla superconducting magnets (Superbends). The radiation produced by these Superbends is an order of magnitude higher in photon brightness and flux at 12 keV than that of the 1.3 Tesla bends, making them excellent sources of hard x-rays for protein crystallography and other hard x-ray applications. At the same time the Superbends do not compromise the performance of the facility in the UV and soft x-ray regions of the spectrum. The Superbend will eventually feed 12 new beam lines greatly enhancing the facility's capacity in the hard x-ray region. The Superbend project is the biggest upgrade to the ALS storage ring since it was commissioned in 1993. In this paper we present a history of the project, as well as the installation, commissioning, and resulting performance of the ALS with Superbends.

INTRODUCTION

October 4, 2001 marked the completion of the Superbend Project — the biggest upgrade to Berkeley Laboratory's Advanced Light Source (ALS) since the synchrotron light source was first commissioned for users in 1993. On that day the ALS facility began user operation with three newly installed Superbends and first light generated from one of these Superbends reached the end station of the first Superbend beamline. With the successful completion of the Superbend project the ALS has transformed itself, greatly increasing its capability and capacity to deliver bright hard x-ray beams (up to 40 keV) to users [1, 2, 4, 3]. There has been a large demand for Superbend beamlines. At the time of this conference 7 of the 12 beamlines have been committed — 3 are in operation for protein crystallography and 2 more under construction, 1 beamline is under construction for tomography and 1 for high pressure diffraction. At the end of the year all 7 will be in operation for users. This still leaves 5 beamlines which have yet to be committed. The 3 protein crystallography beamlines which have been in operation for about one year have performed extremely well and have help to solve many protein structures. With the Superbend upgrade the ALS has greatly extended its capacity and capability in the hard x-ray regime.

The ALS was initially designed to be optimized for the generation of radiation from the UV to Soft x-ray range (10 to 1500 eV). Over the years it has developed a strong user community in this spectral region. At the same time, the ALS saw a large growth in a user community outside of this core region — in the hard x-ray region. Prior to the installation of the Superbends there were two sources of hard x-rays: the normal conducting 1.3 Tesla dipoles and a 2 Tesla wiggler. The wiggler beamline which uses 12 keV photons generated from the wiggler proved to be one of the most productive protein crystallography beamlines in the world demonstrating the capabilities of lower electron energy synchrotrons like the ALS to do hard x-ray science [5]. The success of beamline 5 together with the need for more protein crystallography beamlines worldwide [6] fueled the demand for more hard x-ray beamlines at the ALS. There was also a demand from the tomography and powder diffraction communities demanding even higher energy x-rays (up to 40 keV).

Superbends versus Wigglers

There are several types of synchrotron based sources for generating hard x-rays — bending magnets, wigglers, wavelength shifters, or undulators. Due to the relatively low electron beam energy, 1.9 GeV, of the ALS made the generation of 12 - 40 keV photons impractical with an undulator. Therefore the practical choices were bends or wigglers. At an electron beam energy of 1.9 GeV, the and a Superbend field of 5 Tesla, the Superbend beamlines and have a critical photon energy of 12 keV and are a good source of photons up to 40 keV. In principle the ALS could have chosen to use wigglers to generate hard x-rays. However there were many advantages of the Superbends. First, by replacing normal bends with Superbends, none of the few remaining empty insertion device straight sections were used. Second, the Superbends provided a high capacity—up to 12 new beamlines (four from each bend) versus a wiggler that only can support 3 beamlines. Third, it is possible to perform the powerful technique of multiple-wavelength anomalous diffraction (MAD) on 9 of the 12 Superbend beamlines versus only 1 of the 3 wiggler beamlines. Fourth, the Superbends were higher in flux density than the wiggler (due to the smaller electron beam size) making them a superior source of 12 keV photons for protein crystallography [4]. This meant that the experimental beam time is shorter. Fifth, the total radiation power in the Superbend beamlines is significantly smaller than that of the wiggler making the beamlines simpler. All totaled, the Superbend solution was a cost effective way to greatly increase the hard x-ray capability of the ALS facility.

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† DSRobin@lbl.gov

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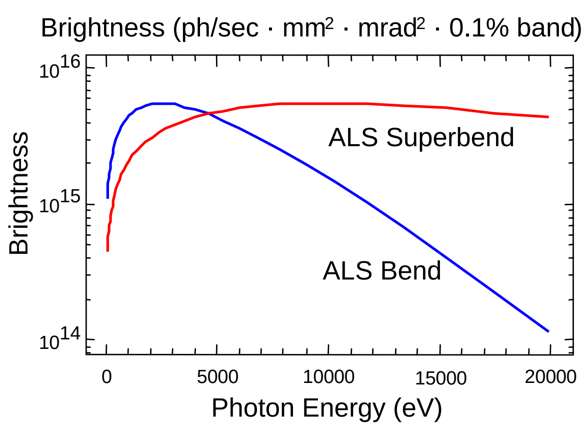

Figure 1: Brightness of a Superbend versus the normal conducting bend

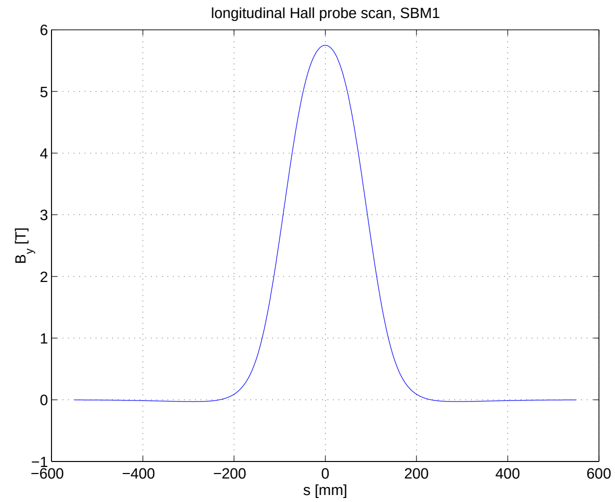

Figure 3: Magnetic field versus longitudinal position at 300 Amps (1.9GeV settings).

Goals and Challenges

The main goal of the project was to modify the storage ring lattice by replacing three of the thirtysix, 1.3 Tesla, normal conducting, 10 degree, bending magnets with three, 5 Tesla, superconducting, 10 degree, bending magnets (Superbends) [9, 10]. This was done by modifying three of the twelve ALS sectors. Fig. 2 shows how each of the 3 sectors was modified to include Superbends. A typical sector without Superbends can be seen in Fig. 2 (top) and one modified to include Superbends is shown in Fig. 2 (bottom). One sees that the central dipole, B2, in the sector is replaced by a Superbend. The Superbend magnetic field versus longitudinal position is plotted in Fig. 3 for the 1.9 GeV settings. The Superbend reaches a peak magnetic field of 5.7 Tesla and is about 5 Tesla at the locations of the four beamlines.

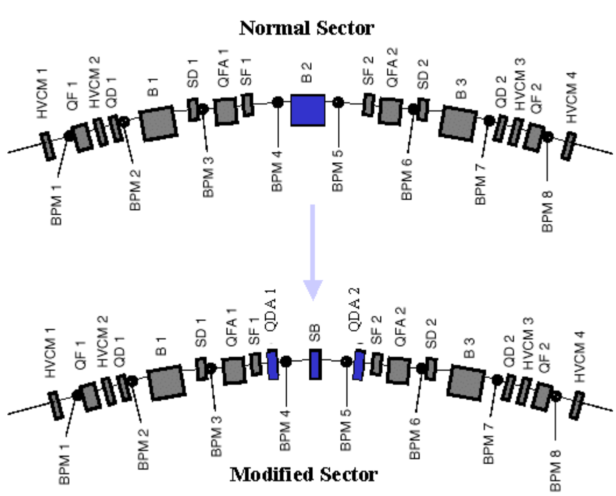

Figure 2: Magnetic layout of a normal (top) and modified (bottom) sector.

Unlike the normal dipoles, the Superbends do not have a quadrupole focusing component. Two new quadrupoles QDA1 and QDA2 are added to the lattice and the QFA quadrupoles in a Superbend sector are put on separate power supplies. It was necessary to make this change in the quadrupole configuration in order to better match the Superbend sectors to the non Superbend sectors to improve the particle beam dynamics.

Choosing Superbends versus wigglers as a source of hard x-rays let the ALS with some unique challenges. This was the first-ever retrofit of superconducting bend magnets into the storage ring of an operating synchrotron radiation source. The Superbends would be an essential part of the storage ring lattice and problems with them not only affect the users of the Superbends but all users at the ALS. Therefore it was necessary to ensure that the transition to Superbend operation was transparent. Superbends needed to be installed and commissioned in a short period and the resulting influence on the existing users should be small. There could be no significant impact on beam orbit stability, fill times, or reliability, brightness, and lifetime.

SUPERBEND PROJECT

The idea of retrofitting the ALS storage rings with high field superconducting magnets to produce hard x-rays was conceived in the early 1990s. In 1995 a project began to see if it was possible design a superconducting coil and core of a magnet that would meet the needs of the ALS [7]. In 1998, based upon the successful tests of a coil and core [8] combined with the increasing demand from the user community, the ALS decided to embark upon the Superbend project [2, 5].

The Superbend project officially began in September 1998 with the formation of the Superbend team. The goal of the team was to ensure a smooth transition to Superbend operation for the existing users. The requirement of a smooth transition drove many of the design choices, some of which are discussed in this paper. The reader is referred to other publications for more details [9, 10, 11, 12, 13].

Beam orbit stabilty is on of the most critical performance parameters for the users. Before Superbends the ALS integrated rms orbit stability in the insertion device straights was about 3 μm horizontally and 2 μm vertically for a frequency range of 1 - 200 Hz. There were two concerns about Superbend operation effecting the orbit stability. They were that orbit jitter would be caused by fluctuations of the powersupply currents of the Superbend and normal conducting bend magnets causing orbit jitter as well as the vibration of the Superbend cryosystem causing the Superbends and neighboring magnets to vibrate also causing orbit jitter. Prior to installation of the Superbends all 36 normal conducting bends were powered by one power supply. In that case powersupply fluctuations resulted in energy changes but not orbit changes. After the installation of Superbends, power supply fluctuations could cause both energy and orbit changes. Therefore both the tolerances of the cryosystem and power supply were very tight and these systems were extensively tested.

Fill times is another important performance criteria for the users. The ALS does not have a full energy injector and therefore before filling the storage ring the electron energy needs to be ramped from 1.9 GeV down to 1.5 GeV where the ring is filled and the ramped back up to 1.9 GeV. Prior to the Superbend upgrade the ramping time was approximately 1 minute in each direction. The Superbend magnet and cryosystm were designed to ramp within that time without quenching. The power supply and control system for Superbends were designed to coordinated well with the other magnets to minimally distort the beam orbit during ramping.

Reliability is another important performance criteria for the users. The Superbends could not significantly impact the total unscheduled downtime of the accelerator. Reliability strongly influenced the choice of cryosystem. A two stage 1.5 Watt Sumitomo cryocooler was chosen for each magnet. Fig. 4 shows a drawing of the cyrosystem. At the high temperature stage there was a nitrogen reservoir and at the low temperature stage there was a helium reservoir. The magnet was conductively cooled with the cryocooler and high temperature Superconducting leads were used between the nitrogen and Helium stages to minimize the heat leak. In the event of a failure of the cryosystem, the magnets could run on external cryogens with a seemless transition between the two modes. In addition a full spare was constructed which could be exchanged in an emergency.

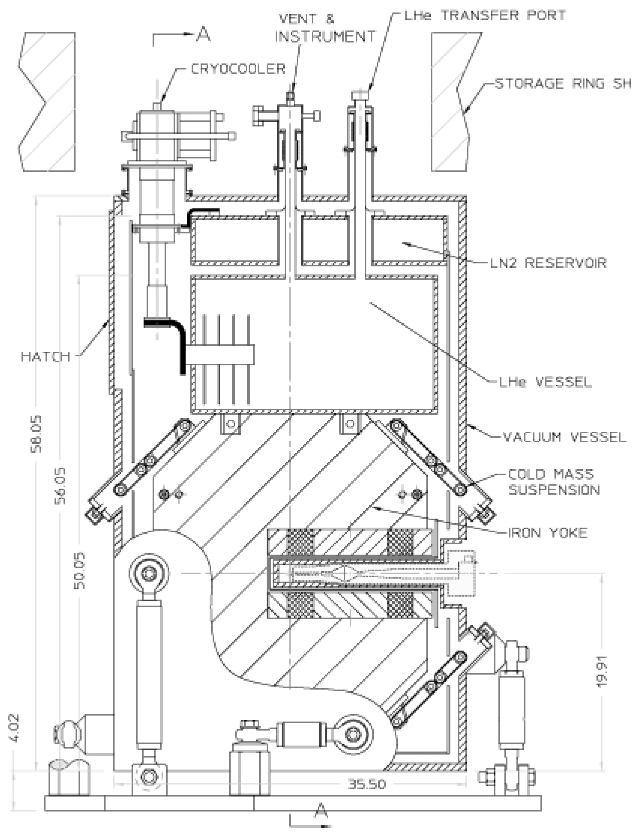

Figure 4: Drawing of the Superbend cryostat and cryocooler

Precommissioning and Beam Dynamics Tests

In order to ensure that the transition to Superbend operation was transparent, the Superbend team adopted the strategy of precomissioning as many subsystems (with and without beam) as possible prior to the actual installation of the Superbends. Much of the work has been described in previous papers.

To minimize the impact on users, the Superbend installation was split into two medium length (6 week) shutdowns. In the first shutdown (which occurred in March 2000) all major components of the project, excluding the actual Superbend magnets were installed [10]. In the second shutdown (which began in August 2001) the Superbends were installed and commissioned [11].

Prior to the Superbend installation, the Superbend systems were extensively modeled and tested. The team performed thorough cryogenic testing [12, 13], magnet measurements [14], vibration testing, powersupply and controls testing [10]. The results of these tests showed that the system was very reliable. During these tests one of the four Superbends was put through the equivalent of 4 years of ramping and cycling with no measurable degradation in cryogenic and mechnical performance. The backup cryogenic system was tested to ensure that the Superbends could transition smoothly to external cryogenic operation in the event of a cryocooler failure [9].

Extensive modeling and measurements were done to ensure that the Superbend upgrade did not impact the lifetime and brightness of the non Superbend users. In terms of brightness, the higher Superbend field necessarily increases the horizontal emittance. Early lattice designs resulted in a doubling of the horizontal emittance. In order not too significantly increase the horizontal emittance, two modifications of the lattice were made. First, finite dispersion

(6 cm) was introduced in the 12 straight sections and second, the QFA and QDAs in the Superbend sectors were adjusted to further reduce the emittance. The result was a small (∼20%) increase in horizontal emittance.

Finally the Superbends could not significantly impact the beam lifetime. The lifetime of the ALS is Touchek dominated and the main concern is that the Superbends would break the lattices 12-fold symmetry, to 3 greatly increasing the resonance excitation resulting in larger beam loss.

Extensive beam dynamics studies were performed primarily to accurately predict and minimize the impact of the Superbends on the lifetime and injection efficiency. We built upon experimental and theoretical studies using the technique of Frequency Map Analysis to study the dynamics of particles in the ALS [17, 18]. Fig. 5 shows the dynamic aperture and on-energy frequency map displayed in amplitude space. The diffusion rate of the particles are indicated by the color. Initial conditions of particles with high diffusion are plotted in red and those with low diffusion are plotted in blue. One can see that the dynamics is well behaved horizontally up to 12 mm which is more than sufficient for a 10 mm injection offset of the ALS.

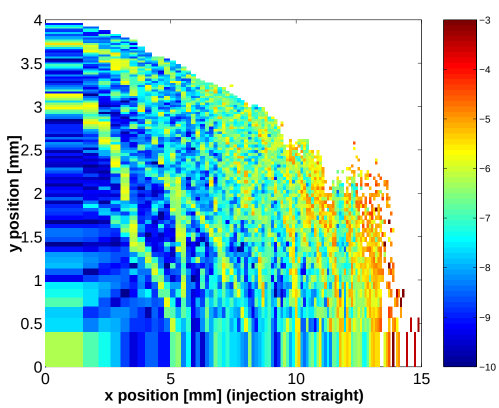

Figure 5: On-energy frequency map of the ALS plotted in amplitude space at the injection point.

The dynamics models were experimentally tested prior to the actual installation of the Superbends. Using the QDA magnets that were installed in the first shutdown, the symmentry of the ring was broken and off energy frequency maps and lifetimes were measured. With the symmetry breaking of the QDAs approximately equivalent to the symmetry breaking due to the Superbends, the dynamic momentum aperture remained close to the RF acceptance at 2.5%. These tests agreed well with our model predictions.

Installation and Commissioning

The installation and commissioning of the Superbends occurred in a 6 week period that began on August 20, 2001 and ended on October 3, 2001. A picture of the first Superbend being installed can be seen in Fig. 6. The installation period lasted for 11 days. During that time 3 normal magnets were removed, 3 Superbends installed, a portion of the injection line disassembled and reinstalled. In addition the new controls, powersupplies, diagnostics, and external cryogenics were installed and tested.

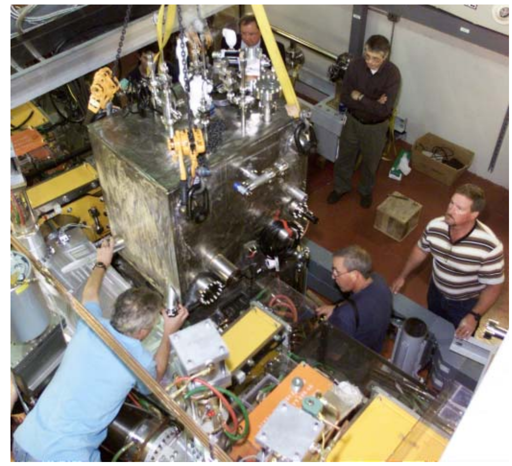

Figure 6: Installation of the first Superbend.

Commissioning began on August 31, 2001 and proceeded faster than expected. First beam was injected within 5 minutes of first attempt, 100 mA stored within 1 hour, first energy ramping with beam later that day, and the impact of the Superbends was evaluated within 2 weeks. The beam was delivered back to users on October 4, 2001 with first Superbend light in the first Superbend beamline. The results of the installation and commissioning are described in detail in another paper at this meeting [11]. During commissioning a lattice with 6 cm dispersion in the straights was adopted. This allowed us to minimize the change in emittance from the Superbends.

Impact of Superbends on the ALS

Looking back one can clearly say that the Superbend project met all, and in many cases exceeded, the project goals. They were installed with no significant impact on the non-Superbend users [11]. Immediately following the installation of Superbends, the lifetime was the same as before, fast orbit stability was the same, slow orbit stability was better, injection and ramping times were comparable and there was a small change in the beam sizes (see Table 1) and no noticable change in brightness. The hard x-ray community is currently making use of the new capabilities and have already achieved some very exciting results [19].

At the time of this meeting it has been nearly 20 months since the ALS Superbend upgrade. In those 20 months the Superbends have been extremely reliable. Superbend system failures have accounted for a small fraction of the total downtime of the ALS. In fact the largest portion of the downtime that was related to operating with Superbends were that the ALS experienced in increase in the failure rate of waterflow meters on photon stops — many of which

Table 1: Comparison of parameters before and after Superbends at the insertion device beamline (.0) and the bend magnet beamlines (.1, .2, .3, .4)

Parameter	Before Superbends	After Superbends
Natural emit.	5.5 rad nm	6.75 rad nm
Energy spread	0.08%	0.1%
Beamline	Hor. beam size	Hor. beam size
x.0	250 μm	310 μm
x.1	50 μm	57 μm
x.2 and x.3	100 μm	100 μm
x.4	60 μm	65 μm
Beamline	Ver. beam size	Ver. beam size
y.0	30 μm	23 μm
y.1	65 μm	54 μm
y.2 and y.3	20 μm	15 μm
y.4	60 μm	52 μm

were located downstream of the Superbends and were presumably failing due to the increased radiation exposure.

The cryosystem has also proven to be very reliable and there has only been one failure. This occurred in March 2003 two weeks prior to a four week scheduled shutdown of the ALS. On one of the Superbends the cryocooler stopped functioning. The Superbends ran with external cryogens for 2 weeks following that failure. The failure resulted in a total downtime of 6 hours. Part of that downtime was due to attempt to restart the cryocooler and part was due to modifications in some controls software to reduce the ramping rate. The operation of Superbends with the cryogens went smoothly with no further downtime. This experience demonstrated the feasibility of operation with cryogens and convinced us that in the case of future failures one should be able to transition between crocooler and cryogenic operation without any downtime.

The three Superbend beamlines have been in production mode for over one year. These initial beamlines were for protein crystallography and have solved more than 200 structures. The performance of the beamline compares favorably to the wiggler beamline. Two more protein crystallography beamlines, a tomography beamline and a high pressure diffraction beamline will be in operation before the end of this year. So this has greatly expanded the capability of the ALS in the hard x-ray regime.

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