NSLS UPGRADE CONCEPT*

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Abstract

To address the growing needs of the NSLS user community we are aggressively pursuing R&D towards a facility upgrade. The present goals are a 3 GeV ultra-low emittance storage ring, tailored to the 5-20 keV photon energy range, that will triple the present NSLS ID capacity, and provide three orders of magnitude increase in brightness over the present brightest NSLS beamlines. To achieve these goals we propose a 24 period TBA lattice, with extensive use of super-conducting small gap undulators. This paper reviews our preliminary design and the key accelerator physics issues.

MOTIVATION, SCOPE AND GOALS

The NSLS facility was designed in the late 1970s and consists of two 2nd generation storage rings emphasizing the production of high flux synchrotron radiation (SR) from bending magnets. These rings were the first DBA (Double Bend Achromat) lattices in the world. The smaller 800 MeV VUV ring covers the photon energy range from far infrared to >0.6 keV. The X-ray ring now operates up to 2.8 GeV, providing photons up to 26 keV, with brightness several orders of magnitude higher than its design value. At this stage, however, there is no foreseeable way to decrease the horizontal emittance significantly below 60 nm which, once the SPEAR upgrade is complete, will leave the NSLS X-ray ring far behind the other three US DOE operated light sources. Additionally, the 8-fold periodicity of the lattice severely limits the number of insertion devices (ID). Today's most important and challenging scientific problems require x-rays with higher average brightness than can be produced by the NSLS.

A significant number of these problems, including a rapidly expanding field of structural biology, are primarily interested in the 5-20 keV energy range. While our user case is still refining we are now intending to provide the maximum average brightness in this energy range emphasizing a high average current multi-bunch operations.

While linac-based SR sources are being considered at this time, acting on the recent recommendations of the DOE Basic Energy Sciences Advisory Committee, that emphasized conservative approach to the NSLS upgrade, we are now concentrating on a 3rd generation storage ring.

The main design goals for the storage ring are:

1) Deliver an average brightness in the range of 10^{20}-10^{21} photons/second/0.1%bw/mm^2/mr^2 for 5-20 keV photons (x10^3 gain over the present NSLS brightest beamline X25).
2) Provide at least 20 undulator straight sections.
3) Meet the user requirements at minimum cost.

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OVERVIEW AND BASIC PARAMETERS

By reducing vertical coupling, 3rd generation light sources can obtain diffraction-limited emittance in the vertical plane, making the brightness inversely proportional to the horizontal emittance. For a given number of straight sections, smaller horizontal emittance is achievable by going to a larger number of bending magnets per period. To meet the needs for more undulator beamlines, we did try to fit a higher periodicity lattice in the existing 170 m long tunnel but, found no solution to provide a competitive light source. It was also felt that a long shutdown for construction would have a severe impact on the present NSLS user program. Consequently the proposed upgrade has a larger circumference ring situated close to the present NSLS and the new Brookhaven Center for Functional Nanomaterials. The new storage ring (NSLS-II) will have a full-energy booster for top-off mode operation.

Based on extensive lattice design studies, providing a horizontal emittance in the 1-2 nm range with a 24 period lattice and 4 m long ID straight sections would require a circumference ~0.5 km. A diffraction limited vertical emittance for 1 Å then fixes the coupling at ~0.5%.

Beam current is usually limited by the SR heating of vacuum chamber components and often specifically by the heat load on the wall of the dipole chamber. With our choice of bending radius and 0.5 A beam current, the SR wall heating of 10 W/m is similar to what is routinely handled in the PEP-II B-factory. Limitations coming from collective effects are described below.

While the combination of increased beam current and reduced emittance will improve the brightness by more than a factor of 100 for the bending magnet users, it is not going to get us all the way to the 1st design goal. We believe, however, that extending the mini-gap undulator (MGU) technology, successfully used in the present NSLS, into a super-conducting regime will accomplish that goal. Assuming device parameters that we believe will be achievable after several years of aggressive R&D, the design ring of 3 GeV should produce continuous coverage up to 20 keV. Brightness curves for these and other IDs are shown in Fig. 1, where NSLS-II ID length is assumed to be 2 m for in-vacuum IDs and 2.5 m otherwise. The small gap super-conducting undulator

(SCU) will be the workhorse of NSLS-II used in up to 18 ID straights. Other IDs may include soft x-ray undulators (SXU) and super-conducting wigglers (SCW, not shown).

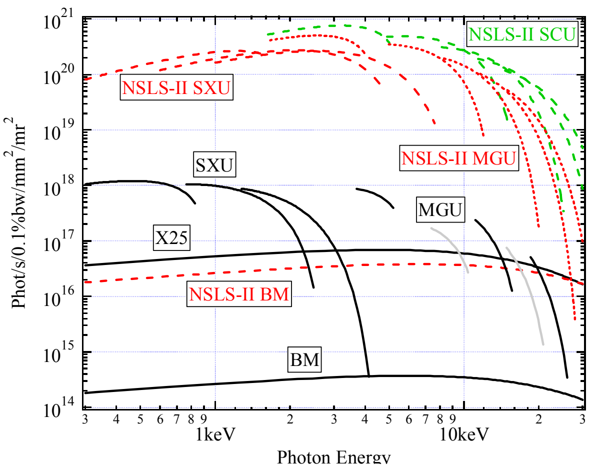

Figure 1: Brightness curves for NSLS-II (dash, color), and for present NSLS (solid black and grey).

Key machine parameters are summarized in Table 1 and are further described in the rest of the paper.

Table 1: Ring Parameters (preliminary)

Nominal Energy	3 GeV
Circumference	523 m
Number of periods	24 TBA
Max. ID Length	4 m
Natural Emittance	1.5 nm
Betatron Coupling	0.5%
Momentum Compaction	0.000187
Bend Radius	7.64 m
Tunes H/V	36.38/13.72
Energy Spread	0.095%
RF Frequency	500 MHz
RF Bucket Height	3%
Natural Bunch Length (rms)	13 ps
Maximum Current	500 mA

SMALL GAP UNDULATORS

Medium-energy rings must use short-period (~ 1 cm) undulators to generate tunable, multi-keV photon beams. Permanent magnet (PM) based, short-period, in-vacuum undulators, which the NSLS has pioneered in the past decade, suffer from low fields, low K values (~1), limited tuning range and incomplete spectral coverage (MGU in Fig. 1.) Due to the relatively high emittance in the present X-ray ring, the holes are partially filled by the even harmonics (shown in grey).

Full coverage of the 5-20 keV range in a 3 GeV ring can be attained with a longer period, in-vacuum MGU having K_{max}>1.32, with its fundamental tunable down to 1.67 keV. This would give the desired coverage using the 3^{rd}, 5^{th} and higher harmonics up to the 11^{th}. An MGU with a 19 mm period, a minimum gap of 5 mm and a phase error of <2° rms (NSLS-II MGU in Fig. 1) could fill this requirement. Its fundamental also covers 1.67-4.0 keV.

SCU technology, under development at the NSLS, other light sources and in industry, promises even better performance in this energy range. For example, coverage from 1.67 to 20 keV with no skips and with higher brightness, could be achieved with an SCU having a 15 mm period, a 5 mm gap (NSLS-II SCU in Fig. 1) and an *average* current density in the windings, J_{avg} ~1200 A/mm^2. This level of J_{avg} is within the realm of NbTi super-conductors. If the gap must be increased, the increased J_{avg} may require more exotic super-conductors. This and other challenging R&D will be addressed by a newly formed 4-lab collaboration (NSLS, SLAC, ALS and APS).

LATTICE AND MAGNETS

The candidate lattice we are now considering to meet the design goals for the NSLS upgrade is a 24 period Three Bend Achromat (TBA). Although many light sources, including the X-ray ring at the NSLS, give up the achromatic condition to achieve lower emittance, this condition does minimize the impact of undulator field change between the users. The TBA lattice is quite flexible with higher emittance tunes yielding lower chromaticity, for the day one lattice. Finally, the TBA lattice is the lowest multiplicity of bend magnets designs that can achieve the isochronous condition without breaking the lattice periodicity. This preserves an option of a possible future upgrade to a linac-based technology.

The lattice assumes gradient dipoles used to reduce the length of a period. To provide additional flexibility, three dispersion quadrupoles are used to vary the lattice properties without giving up on the achromatic condition. By changing the outer two dipole magnets to half the bending angle and length, a lower emittance was achieved. This could be optimised further in later designs closer to the optimum ratio of $\sqrt[3]{3}$:1 [1], but a simple 2:1 split was used so far.

The low emittance TBA lattice shown in Fig. 2 has a natural emittance of 1.5 nm but with large chromaticity. Three families of chromaticity correcting sextupoles are shown to reduce the magnitude of the chromaticity or make it slightly positive. Two families of harmonic correction sextupoles are installed in the dispersion free region to reduce the impact of the chromatic correction sextupoles on the dynamic aperture. The dynamic aperture in the TBA lattice is limited by many competing higher order non-linear resonances coming from chromatic sextupoles. Several design codes [2-3] attempt to minimize these driving terms by phasing the sextupoles in the lattice. The five families provided in this design provide a dynamic aperture sufficient for injection into an ideal lattice. Future designs will break the 24-fold periodicity, providing additional harmonic sextupoles families for expansion of the dynamic aperture with errors, as was used in the Swiss Light Source [4] and proposed for the DIAMOND ring [5].

Space is provided in the straight section for correction magnets and injection bumps. Some correction magnets are combined in the sextupole magnets to save space. The correction magnets in the straight section are capable of deflecting the closed orbit inward by ~1 cm, to avoid the SR of the upstream dipole magnet. Additional correctors in the dispersion region and dipole back-leg windings will provide closed orbit correction.

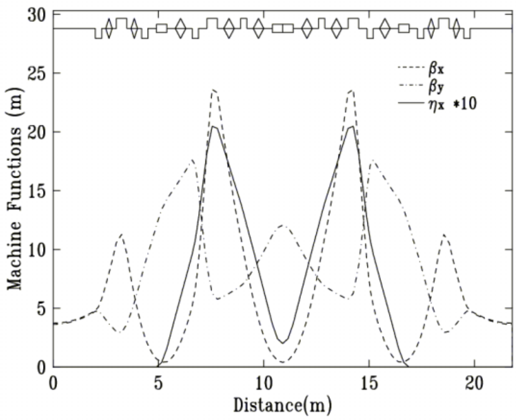

Figure 2: NSLS-II magnet layout and lattice functions.

RF SYSTEM

The RF system must deliver about 0.8 MW RF power for SR losses when the lattice is loaded with its full complement of insertion devices (18 SCUs and 2 SCW is assumed). Additional power is required to sustain the fields in the cavities, for RF losses, and for power lost to higher-order modes (HOMs), resistive-wall, etc. The cavities together must also be able to sustain approximately 2.8 MV voltage to provide 3% momentum acceptance, which we presently use as a baseline.

The choice of cavity technology, either normal-conducting or super-conducting, is determined by their ability to provide RF voltage, maximum power delivery, the spectrum of trapped higher-order modes and their damping, and other considerations. Super-conducting (SC) RF cavities are available that are capable of providing the full accelerating voltage from one cavity. They also have a very limited number of trapped HOMs, which are well damped. Proven operational input-coupler power figures [6] (e.g., CESR and KEK-B cavities) imply three cavities are required to meet the 0.8 MW RF power figure. With regard to available room-temperature cavities, a minimum of three are needed to meet the 2.8-MV requirement; three are more than adequate to deliver the RF power. So, while three cavities is a baseline requirement using either technology, further development and improved fabrication techniques of input couplers for SC cavities may obviate the need for a third cavity. For these and other reasons, SC cavities are proposed.

COLLECTIVE EFFECTS AND LIFETIME

Although self-stabilizing, the longitudinal microwave instability is important since the energy-spread reduces the brightness, especially for higher undulator harmonics. The Boussard criterion limits the broad-band impedance to $|Z/n|_{max}$~0.1 Ω (assuming 0.86 mA/bunch due to 1/3 of the ring ion clearing gap). This should be possible to achieve via careful impedance control. The threshold could be further raised using harmonic RF. Since up to 1 m is reserved for SCU/MGU tapers, they will not present significant impedance.

Due to multiple small-gap devices, transverse coherent single bunch instabilities, such as TMCI and microwave, are very important. While raising the chromaticity could circumvent them [7], this will ultimately limit the dynamic aperture and/or require strong sextupoles. We are currently planning an R&D program to spec and design an MGU chamber with acceptable transverse impedance. We are also trying to extrapolate from the experience with small gap devices at NSLS and other light sources.

Our preliminary estimates do not show significant coupled-bunch instability due to resistive wall. The effect of small ID gaps is partially compensated by small beta functions and, in case of SCU, reduced wall impedance. Instabilities due to HOM are less expected due to SC RF.

For the intra-beam scattering (IBS) we are probably within parameter range already probed by existing facilities, (ATF-KEK, ALS, etc) and we do not expect the IBS to affect the multi-bunch operation. ZAP and SAD show only a few % emittance blow-up at 1.5 mA/bunch.

The acceptance at the edge of a 2-m long MGU is 1.6 10^{-6} m-rad. For 1 nTorr N_2 equivalent pressure, this results in lifetime of ~40 hours. Similarly, bremstrahlung lifetime is about 50 hours. As a result, similar to other 3rd generation light sources, the lifetime is expected to be Touschek dominated. Calculations give a half-life of less than 2 hours. While this should not be a problem running in a top-off mode, it requires putting some thought into radiation shielding. Again, a harmonic RF system could alleviate this problem.

Detailed lifetime calculations are needed to carefully take into account physical and dynamic apertures, non-linear synchrotron motion, etc.

SUMMARY AND FUTURE WORK

We are at the very beginning of this project. The most pressing R&D issues are:

- Mini-gap super-conducting undulators.
- Lattice optimisation for dynamic aperture.
- Collective effects, and especially the microwave and transverse single bunch instabilities.
- Booster design and injection details.
- Orbit stability and feedbacks.

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