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The Revitalized NSLS VUV Ring

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Abstract. A status report on the revitalization of the NSLS VUV ring will be presented, concentrating on three areas:
1) the four infrared ports (U2A/B, U4IR, U10A/B, and U12IR),
2) conversion of out-of-date toroidal grating monochromators to spherical grating type (U4A, U7A, and U12A), and
3) new insertion device beamlines (U5UA and U13UB).
All of these beamlines were designed (new ones) or upgraded (old ones) to serve a specific scientific need represented by the PRTs (both NSLS and non-NSLS based) involved. Therefore, an overview of the scientific programs served by these new beamlines will be given, as well as a summary of the beamline optical designs and operating performance.

INTRODUCTION

During the past five years or so, a concentrated revitalization program has taken place at the NSLS VUV ring. This effort, which has been driven by the scientific needs of new scientific programs, has resulted in a number of new or upgraded beamlines which are described generally in this paper and more specifically in other papers in this volume. This revitalization effort consists of efforts in three categories distinguished broadly by wavelength range:

1) the four infrared ports (U2A/B, U4IR, U10A/B, and U12IR),
2) conversion of out-of-date soft x-ray toroidal grating monochromators to spherical grating type (U4A, U7A, and U12A), and
3) new insertion device VUV beamlines (U5UA and U13UB).

Fig. 1 is a plan view of the NSLS VUV ring showing only the beamlines which have been constructed or upgraded since the mid 1990's (with the exception of U4IR, which was commissioned in 1987).

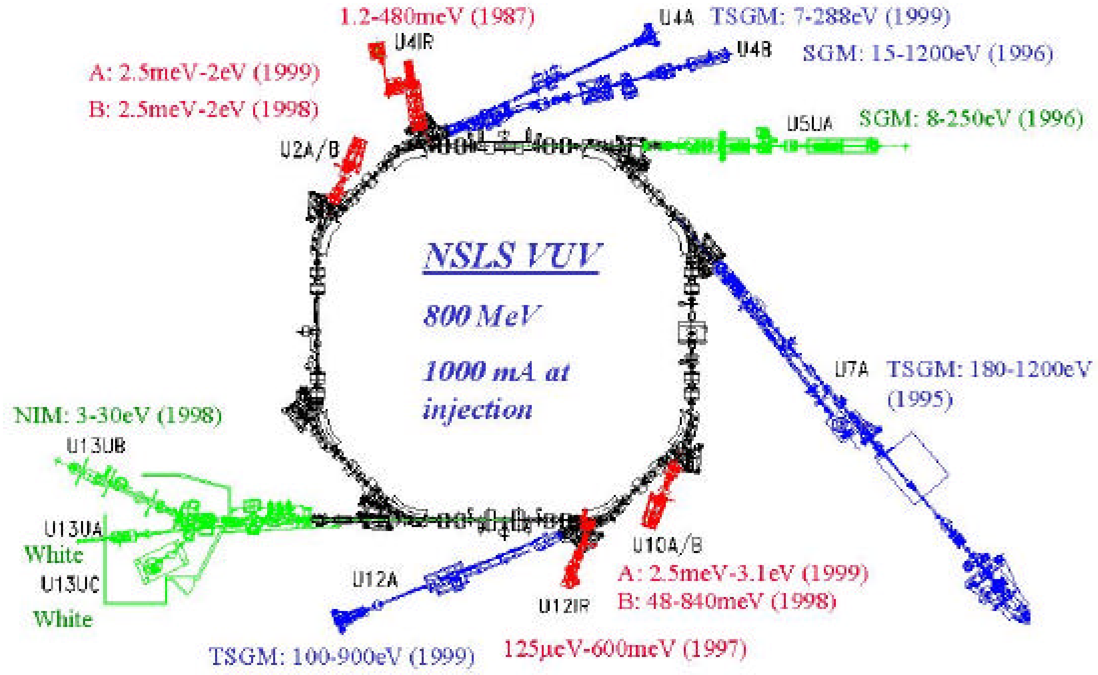

FIGURE 1. New and recently upgraded NSLS VUV ring beamlines. Photon energy ranges covered and commissioning date (year, in parentheses) are indicated. Endstations are *not* shown.

INFRARED BEAMLINES

The infrared beamports and beamlines on the NSLS VUV ring are the result of continuous development dating back to the NSLS Phase II construction which took place in the late 1980's. The first NSLS infrared beamline, U4IR, designed and built under the direction of Gwyn Williams (NSLS), is a high brightness far infrared beamline on a 90 x 90 mrad^2 port (see below) which serves a diverse international community of surface spectroscopists. In late 1992, a standard VUV bending magnet port (12mrad horizontal × 8mrad vertical) was instrumented for infrared use, by Gwyn Williams and Larry Carr (who was with Grumman Research Center at the time), in collaboration with the Carnegie Institute of Washington, for mid-infrared microspectroscopy of electronic materials and systems at extreme pressures. In 1995, Jerry Hastings (NSLS) suggested the possibility of increasing the vertical opening angle of selected VUV ring bending magnet ports to 40mrad. This modification was made to the U2 front end in late 1996, thereby delivering diffraction-limited radiation out to 0.5mm wavelengths and greatly enhancing the scientific capability in the mid-infrared. Since these ports deliver 80mrad horizontally, they are most efficiently split into two 40 x 40 mrad^2 ports (U2A and U2B). Beginning in 1997, construction on the complement to the U4IR and U2A/B beamlines was begun at U12IR (90 x 90 mrad^2) and U10A/B (each 40 x 40 mrad^2). These three beamlines were commissioned in late 1998 and early 1999.

If one is interested in designing a synchrotron-based infrared source, the most important source quantity to be preserved is its brightness, as is true of any photon source illuminating an optical system. The average diffraction-limited brightness of a synchrotron bending magnet source, where the average is taken over $4\psi_{rms}$ and $\psi_{rms} = 0.83(\lambda/2\pi\rho)^{1/3}$ is the diffraction-limited rms vertical opening at wavelengths $\lambda >> \lambda_c$ and $\lambda_c = 4\pi\rho/3\gamma^3$ is the critical energy, is (1)

$$B = \frac{Flux}{Phasespace(H \times V)} = 3.8 \times 10^{14}\ photons/\mathrm{sec}/0.1\%BW/mm^2/steradian\ \frac{I[A]}{l^2[mm^2]}. \quad (1)$$

This average brightness is evidently independent of all source parameters except the beam current I and the wavelength λ. In terms of angle, one wants to collect at least $\pm\psi_{rms}$ in the horizontal and vertical planes. The angle ψ_{rms} is a quite weak function of the bending magnet radius ρ. For example, at the long wavelength end of the far-infrared region, ~1cm^{-1}, ψ_{rms} is 80mrad for short radius rings such as the NSLS VUV ring, but only decreases to 30mrad for the ~40m radius typical of recent high energy storage rings such as the APS at ANL. The choices of vertical collection angle for the NSLS infrared beamlines, 90mrad for the far-infrared beamlines U4IR and U12IR and 40mrad for the mid-infrared beamlines U2A/B and U10A/B, produce practical long-wavelength limits of 0.1cm^{-1} and 20cm^{-1}, respectively.

The wavelength range of each infrared beamline is determined by the overlap of the source wavelength range discussed above and the wavelength range covered by the beamline optics. These typically consist of transport and focusing and, usually, a commercial FTIR spectrometer. The transport and focusing mirrors transmit into the visible and UV range, even at large angles of incidence, and do not pose a limit to infrared beamlines. The window which separates the beamline from machine vacuum is generally fabricated from high quality diamond, which transmits wavelengths greater than ~0.25μm (i.e. all of the infrared). The wavelength range of the infrared beamlines, therefore, is generally determined by the choice of spectrometer. The photon energy ranges covered by the various NSLS IR beamlines (U2A/B, U4IR, U10A/B, and U12IR) are indicated in Fig. 1. For details regarding the optical layout and types of spectrometers presently in use on the NSLS IR beamlines, see their web pages, links to which can be found at the NSLS web site, nsls.bnl.gov (User Information; Beamlines). For a general review of the infrared programs at the NSLS, see reference (2).

One rather unique infrared capability at the NSLS is the existence of a high repitition rate tunable Ti:sapphire infrared laser which can be synchronized to the RF frequency of the VUV storage ring and delivered to various beamlines by optical fiber. This capability enables various kinds of pump-probe timing experiments in the infrared, a program which is led by Larry Carr (NSLS). This is especially useful in the far infrared, where conventional infrared sources are much less bright than a storage ring. From the accelerator side, these experiments require pulses which are as short and as stable as possible. Recently, Steve Kramer (NSLS) has demonstrated that the electron bunch length in the NSLS VUV ring can be made quite stable, independent of beam current, using a simple feed forward technique. As shown in Fig. 2, the change in bunch length with beam current can be held to 5fs/mA over a factor of nearly two in beam current. Note that the average length of the bunches shown here can be made significantly shorter, for timing experiments, by proper powering of the fourth-harmonic (211MHz) RF cavity.

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FIGURE 2. Average electron bunch length (fwhm) of the NSLS VUV ring as a function of beam current, for two fill modes: normal (triangles) and "constant bunch length" (circles). The best-fit straight lines to these data (solid black lines) intersect at zero beam current. Slopes are indicated. Source: Steve Kramer (NSLS).

SOFT X-RAY BEAMLINES

A majority of the original beamlines designed and built for the NSLS VUV ring in the early 1980's were dedicated to soft x-ray spectroscopies of various types. A significant number of these beamlines were designed using the then-popular toroidal grating monochromator (TGM) design. It is now well known that the TGM design suffers from inherent resolution-degrading optical aberrations, most notably astigmatic coma which depends on the square of the sagittal filling of the grating. Since the groundbreaking development of the so-called spherical grating monochromator (SGM) in the mid-1980's by Chen and Sette (3), the SGM has been the simplest optical design, mechanically, for achieving high photon energy resolution. Our soft x-ray beamline upgrade program in the 1990's has consisted of implementing the SGM optical design by using the simplest and fewest alterations of the existing TGM beamlines. The result of this design process is what we dub the TSGM, which stands for Toroidal mirror SGM. In this design, there is no deflection of the synchrotron beam in the horizontal direction, a characteristic of the "standard" SGM design but one which is not compatible with the layout of the standard TGM design. In place of the Kirkpatrick-Baez (KB) collecting and focusing mirror pair used in the "standard"

SGM (KBSGM), a single toroidal mirror is used. Otherwise, the TSGM and KBSGM optical designs are identical. As will be shown below, the transmission of the TSGM optical system is comparable, or even slightly larger than, that of the KBSGM up to a horizontal acceptance of approximately 10mrad. By preserving the TGM linear beamline layout, the TSGM design retains ("recycles") all of the mirror and grating manipulators and vacuum chambers, pumps, etc., resulting in considerable cost savings.

The locations and photon energy ranges of the KBSGM beamline (U4B) and the TGM-to-TSGM upgraded beamlines at the NSLS (U4A, U7A, and U12A) are shown in Fig. 1. U7A and U12A are 174° included angle soft x-ray TSGM beamlines covering the 200-1200eV and 100-800eV photon energy ranges, respectively. Three endstation positions exist at the U7A beamline, one unfocused and two focused by toroidal mirrors which focus the soft x-rays to <1mm spot size. Owing to floor space limitations, the U12A beamline has only one, unfocused, endstation position. Both U7A and U12A are used for electron spectroscopy and fluorescence spectroscopy in the Carbon K-, Oxygen K-, and transition metal L-edge ranges. In addition, U7A extends up to the Al K-edge (1486eV), whereas U12A extends down to the Si L-edge (100eV). U7A is used for soft x-ray photoemission of materials of chemical interest (e.g. complex surface intermediates important in catalysis), soft x-ray NEXAFS of materials of industrial interest (e.g. polymer surfaces and their interfaces), and soft x-ray fluorescence detector development. U12A is used for soft x-ray photoemission of molecular adsorbates on catalytic surfaces of interest to the automotive industry. Quite recently, the TGM-to-TSGM upgrade of the U4A beamline, a 160° included angle beamline covering the 8-250eV photon energy range, was completed. The U4A beamline features two endstations, one focused and one unfocused. The upstream endstation is dedicated to lineshape analysis of shallow core levels in angle-integrated photoemission, while the downstream endstation features one of the earliest "high-angle-resolution" angle-resolved photoemission systems.

The original U7A and U12A TGMs were based on a variant (4) of the "standard" TGM (5) in which the exit slit was made movable, along the optical axis, in order to track the photon-energy-dependent focal length in first inside diffraction order, which varies by approximately 1m over the photon energy range covered by one grating. The original implementation also minimized the astigmatic coma aberration by selecting the sagittal radius of the toroidal first mirror such that its horizontal focus lay just upstream of the grating, thereby minimizing the sagittal footprint on the grating. These advances pushed the theoretical (i.e. for perfect toroidal gratings, which are difficult to manufacture) resolving power of the TGM to approximately 1000 in the soft x-ray range, but only at small (≤1.5mrad) sagittal acceptance. An unwanted byproduct of this design is that the grating necessarily magnifies the beam in the sagittal direction, by a factor of 7:1, typically, which leads to a quite large sagittal beam size at the exit slit and an even larger value further downstream. In contrast, the SGM optical design has a demonstrated resolving power of 5000-10000 in the soft x-ray range, even at 15mrad horizontal acceptance (and probably higher), for realizable (0.5arcsec 2-σ figure error) spherical gratings.

Since the TSGM and SGM designs are identical downstream of the entrance slit, it is the collecting and focusing toroid in the TSGM which is to be compared with the KB mirror pair of the “standard” SGM. The function of these optics, in either design, is to collect as much SR light as the grating can accept and focus it quite astigmatically: tangentially (vertically, in most cases) on the entrance slit with ~1:1 magnification and sagittally just downstream of the exit slit (the position, generally, of the first experimental endstation) with ~5:1 magnification. One advantage of the single mirror in the TSGM design is the elimination of one reflection compared to the KB SGM design, which can be quite significant (up to a factor of 2) in the soft x-ray range. On the other hand, the toroidal mirror suffers from coma aberration (smile-shaped image) at the vertical focus (i.e. at the entrance slit), resulting in a concomitant loss of flux. Note that this optical aberration does not affect the photon energy resolution of the TSGM beamline: the entrance slit defines the source seen by the grating, as in the KBSGM design. The optical efficiency of the toroidal mirror in the TSGM design is slightly photon-energy dependent, via the SR vertical opening angle, but a typical value in the soft x-ray range for 10mrad horizontal collection is 60% of that of the corresponding KB pair in the KB SGM design, as shown in Fig. 3.

FIGURE 3. Beam footprints at the entrance slit of the KBSGM (right) and TSGM (left) soft x-ray beamline optical designs for 10mrad horizontal illumination. In both cases, the first optic is ~2.5m from the source point, and the vertical opening angle is that for a photon energy approx. one-half the critical energy of the NSLS VUV ring. Vertical profile comparison of the two designs (center). Ray tracing performed using SHADOW (6).

Thus, the overall transmission of the TSGM, compared to the KB SGM, is 0.6/0.5=1.2 (for 10mrad horizontal acceptance). Larger horizontal angles would be almost completely lost at the entrance slit in the TSGM design, so the overall efficiency comparison at 15mrad horizontal acceptance would be TSGM/KBSGM = $1.2\times10/15=0.8$. From a manufacturing perspective, the desired toroidal mirror for a typical TSGM beamline at the NSLS VUV ring has a major radius of ~40m and a minor radius of ~200mm.

INSERTION-DEVICE-BASED VUV BEAMLINES

The NSLS VUV ring has two straight sections available for insertion devices, U5U and U13U, both of which are low-field-error hybrid planar undulators. U5U (7) is a 27-period, 7.5-cm device with an on-axis magnetic field $0.05T < B < 0.45T$ ($0.35 < K < 3.2$) and a fundamental photon energy range $11.3eV < h\nu_1 < 70eV$. U13U is a 22-period, 10-cm device with an on-axis magnetic field $0.05T < B < 0.72T$ ($0.4 < K < 6.7$) and a fundamental photon energy range $2.2eV < h\nu_1 < 50eV$. Both insertions are being operated in their low-K (undulator) regime utilizing the first, third, and sometimes fifth harmonics. The locations and photon energy ranges of the beamlines served by the NSLS VUV insertion devices (U5UA, U13UA,B, and C) are shown in Fig. 1.

The optical design of the U5UA undulator beamline is based upon a four-grating 3.5m spherical grating monochromator (SGM) which operates in the photon energy range 10-250 eV. Its high brightness, especially in the lower half of this energy range, makes it an ideal tool for Spin-Polarized Photoemission Spectroscopy (SPPES) and other brightness-demanding VUV experiments. The U5UA beamline features a permanently-mounted SPPES endstation, based upon a spin- and angle-resolved photoemission spectrometer, to carry on a scientific program to study the electronic structure and magnetic properties of thin ferromagnetic films. In late calendar 2000, we expect to commission an extension of this beamline with further refocusing optics to serve a second experimental endstation position for general use. The optical design of this beamline, including comparisons with the TGM-based beamline which it replaced, are presented in reference (8). Further discussion of the optical design and examples of SPPES and magnetic linear dichroism (MLD) results from ferromagnetic surfaces is provided in reference (9). We are in the process of adding a four-reflection-type circular polarizer located downstream of the monochromator exit slit, which will open up new experimental areas for VUV research at NSLS.

The only difference between the optical design of the U5UA beamline and that of the TSGM beamlines discussed in the previous section is in the first mirror. In the case of U5UA, the opening angles of the undulator source are small enough that the first mirror does *not* need to provide any sagittal focusing. Rather, the only sagitally-focusing element in the entire beamline is the refocusing mirror. In the case of the first experimental endstation, the refocusing mirror is strongly demagnifying (~14:1), thereby creating a sub-mm spot size at the sample position which matches efficiently to the electron optics of the spin-resolving electron energy analyzer (8). Thus, the first mirror in the beamline provides only tangential focusing which, for the small undulator-source opening angles, is efficiently performed by a spherical mirror.

The U13U insertion device as served a variety of projects since the early 1980’s, ranging from R&D work on FELs (1980’s) to soft x-ray spectroscopy (early 1990’s) to high brightness VUV electron spectroscopy since 1998. The U13UB beamline, dedicated to high brightness science in the 3-30eV photon energy range, is based on a 3m normal incidence monochromator (NIM) provided by McPherson, Inc. (10).

Commissioned in mid-1998, this beamline has been utilized, to date, entirely for high-resolution angle-resolved photoemission spectroscopy by the Peter Johnson and his group in the BNL Physics Department. For a summary of the U13UB beamline design and early results of the photoemission program, see reference (11). See also reference (12) to more recent work. The U13UA and U13UC branches are presently dedicated to VUV projection lithography development (Lucent Technologies).

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