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Design of a Dedicated Beamline for X-ray Microfocusing- and Coherence-Based Techniques at the Advanced Photon Source

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Abstract

A dedicated insertion-device beamline has been designed and is being constructed at the Advanced Photon Source (APS) for development of x-ray microfocusing- and coherence-based techniques and applications. Important parameters considered in this design include preservation of source brilliance and coherence, selectable transverse coherence length and energy bandwidth, high beam angular stability, high order harmonic suppression, quick x-ray energy scan, and accurate and stable x-ray energy. The overall design of this beamline layout and the major beamline components are described. The use of a horizontally deflecting mirror as the first optical component is one of the main feature of this beamline design, and the resulting advantages are briefly discussed.

I Introduction

The high brilliance synchrotron x-ray beams that will be provided by the Advanced Photon Source currently being constructed provide a unique opportunity for developing microfocusing- and coherence-based techniques and applications. The combination of the high brilliance x-ray beam with ever improving high performance x-ray microfocusing optics being developed around the world will enable the development of x-ray microprobes with unprecedented capabilities. Spatially resolved elemental analysis with submicron resolution and femtogram sensitivity may be routinely obtained. The spatial distribution of electronic or chemical states in a material system can be mapped using a x-ray spectromicroscope like the one developed for the soft x-ray region. Spatially resolved microdiffraction can be applied to study structural variation in a sample, e.g., strain distribution or crystallographic phase distribution.[1,2] Three dimensional tomography with submicron resolution similar to that developed for the soft x-ray

region may be developed for the hard x-ray region.[3,4] The development of coherence-based techniques such as x-ray interferometry, x-ray holography,[5] and speckle correlation spectroscopy[6,7] will extend the unique capabilities demonstrated in the longer wavelength region into the x-ray spectral region.

The dedicated insertion-device beamline being constructed at Sector 2 of the Advanced Photon Source (APS) is for the development of x-ray microfocusing- and coherence-based techniques and applications. The overall design of this beamline layout and the major beamline components are described.

II Beamline Layout and Major Optical Component

II.1 A Brief Overview

The layout of the key optical and vacuum components of beamline 2-ID-D/E is shown in Fig. 1. It is one of three beamlines that branch off via mirrors from the same ID front end. The main design objective of this branch line is to provide spectral and coherence properties required by the development of x-ray microfocusing optics and related techniques and the development of coherence-based x-ray techniques in the 3 - 40 keV spectral region. Important parameters considered in this design include preservation of source brilliance and coherence, selectable transverse coherence length and energy bandwidth, high beam angular stability, high order harmonic suppression, quick x-ray energy scan, accurate selection of x-ray energy, and stable x-ray energy setting.

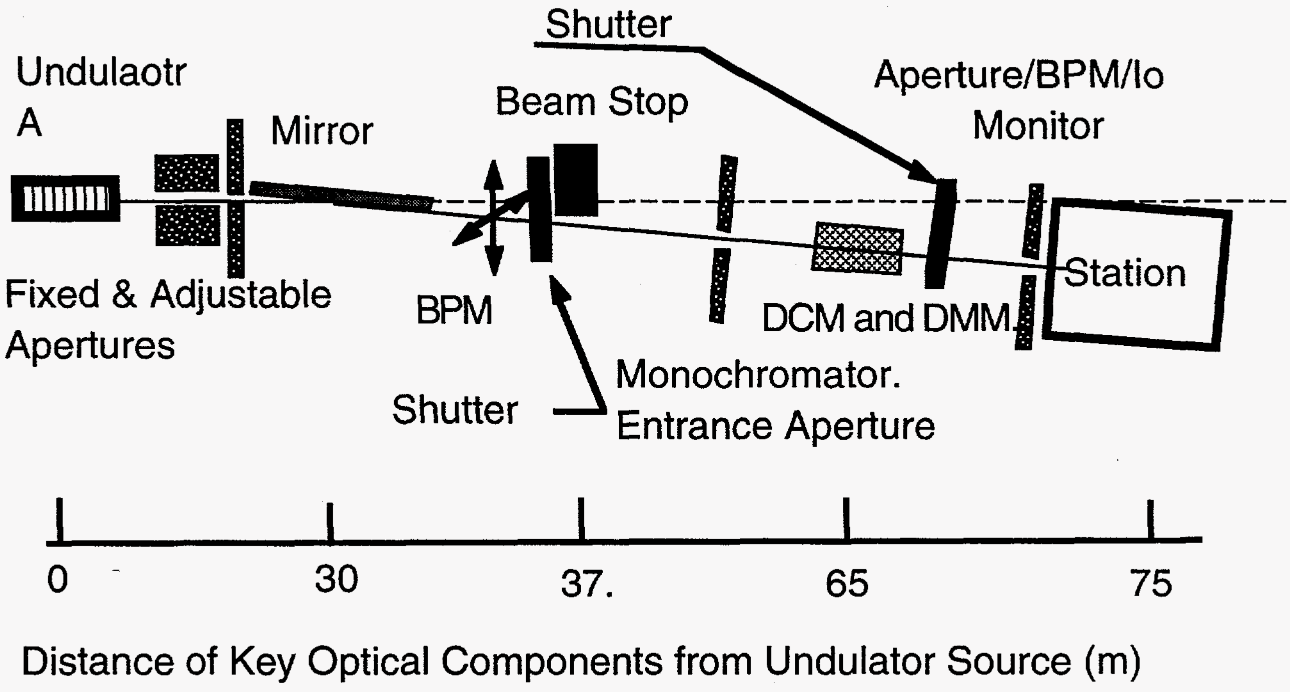

Fig. 1 Layout of the major beamline optical components. (BPM: pink beam position monitor, DCM: double crystal monochromator, DMM: double multilayer monochromator)

II.2 Beamline Front End

The front end for the 2-ID beamline is similar to other standard APS ID front ends except that the last component is a fixed-aperture/differential-pump combination instead of a Be window. Windowless operation is required to obtain high throughput for x-rays of energy less than 4 keV and to avoid degradation of wavefront due to vacuum barriers. The water-cooled fixed aperture (4.5 x 4.5 mm) located at 27.25 m from the center of the insertion device (ID) straight section is used to transmit only the central core of undulator radiation and reduce the unwanted power outside the central core. For the standard undulator A, which is the radiation source of the beamline, the fixed aperture reduces the total power from 4.4 kW to 2.2 kW at a closed gap of 11.5 mm. The angular acceptance of the synchrotron x-ray beam of the fixed aperture is 165 μrad for the undulator A.

II.3 Adjustable Aperture

The differential pumping system is followed by an adjustable aperture (AA) (an APS standard component L5-80) at 28.25 meters from the center of the ID straight section. The adjustable aperture is used to reduce the effective source size to increase lateral coherence length for coherence-based x-ray techniques and to improve spatial resolution in microfocusing-based x-ray techniques. The adjustable aperture is also used as an entrance aperture for the horizontal deflection mirror to be described below. It consists of two L-shaped knife blades that are water cooled. Each blade can be translated in two orthogonal directions over a distance of 8 mm with an accuracy of 5 microns and a resolution of 1 micron. Thermally induced aperture change is designed to be less than 5 microns.

For small aperture settings (aperture size less than about 100 μm), the aperture acts as an effective source size for the focusing optic in the experimental station. The lateral coherence length of the undulator radiation can be increased by using a small aperture size. For example, for an aperture size of 40 μm, the lateral coherence length of a x-ray beam in the experimental station would be improved approximately by a factor 4 and 13 in vertical and horizontal directions, respectively.

II.4 Horizontal Deflection Mirror

The use of a horizontally deflecting mirror (M1) as the first optical component is one of the main features of this beamline design. The beam reflected by a mirror is referred to as pink beam in this paper. The mirror has three parallel stripes of reflecting surfaces, with one being the polished Si substrate surface, and the others being coated with Pt and Rh. The mirror is located 30 m from the ID source. The mirror deflects the incident undulator radiation toward the storage ring and the grazing incidence angle is 0.15°. The advantages resulting from this mirror are presented in detail in two separate papers in this proceeding and a brief summery is provided below.

First, the peak radiation heat flux and total power on the downstream optical and nonoptical components are substantially reduced and thus the thermal designs for those components are significantly simplified. For example, a water-cooled first crystal in conventional, symmetric double-crystal monochromator (DCM) geometry can be used. Second, the radiation shielding requirement is substantially reduced to a level that is similar to that for a beam monochromatized by a crystal.[8] As a consequence, the beamline layout of the optical components downstream of the mirror can be optimized without additional shielding and thus the construction cost and maintenance effort are substantially reduced. For example, undulator radiation up to 32 keV can be delivered to the experimental stations with little brilliance degradation, and a DCM with a small offset between the incident and diffracted beam can be used as a quasi-channel-cut monochromator with small displacement of the diffracted beam for an energy scan. Third, the high order harmonics of the undulator radiation are significantly suppressed when an appropriate mirror coating is selected. This high order harmonic suppression is particularly important for high energy storage rings like the Advanced Photon Source (APS). Finally, horizontal deflection was selected for the following three reasons: (1) preservation of the source brilliance and the beam coherence in the vertical direction because the horizontal divergence of the undulator radiation is much larger than that in the vertical direction and the mirror tangential slope error is dominantly responsible for the degradation of beam brilliance, (2) reduction in gravity-induced slope errors because the gravity-induced sagging is parallel to the reflecting surface, and (3) maintenance of the standard beam height facilitating utilization of standard beamline components and subsequent survey and alignment.

The M1 mirror is used together with the fixed and adjustable apertures to reduce the total power and the power density incident on the first crystal or multilayer of a monochromator to achieve good angular stability and coherence preservation.

II.5 Pink Beam Position Monitor

The pink beam position monitor will be used for the alignment of the M1 mirror and monitoring the deflection angle of the beam reflected by M1. A standard APS white beam position monitor has been procured, and this monitor will allow us to monitor the reflected beam with an angular resolution better than 1 microradian. If necessary, an active feedback system using the beam position monitor can be set up to maintain a fixed mirror deflection angle.

II.6 Monochromator Entrance Aperture

The pink beam adjustable aperture upstream of the double-multilayer monochromator (DMM) will be used as the entrance aperture to both the DMM and the DCM to reduce the total power incident on the monochromators. When it is used with the DCM, improvement may be obtained in the energy resolution and spectral purity of the diffracted beam.

II.7 Monochromators

Various degrees of monochromatization will be available for experiments. In addition to the mirror-reflected undulator beam, beams monochromatized by either a DMM or a DCM can be selected by a user. Both monochromators will be configured to have a fixed beam exit in both spatial position and angular direction. The DCM will be used for experiments that require high resolving power, such as microspectroscopy, microdiffraction, differential-contrast microimaging, and coherence- and interference-based experiments. The moderate resolving power of the DMM will be used for microanalysis and micro-Laue diffraction to increase the flux at the focus of a Fresnel phase zone plate or other suitable microfocusing optics.

The DCM and DMM monochromators are located at about 64 and 65 meters from the source, respectively. The combination of this large distance and the power filtering of M1 reduces the maximum radiation heat flux at normal incidence to less than 13.3 W/mm^2, which is about a factor of 13 less than the comparable raw undulator heat flux of 191 W/mm^2 at a monochromator-source distance of 28 meters. The calculated heat flux incident on the first crystal of a Si DCM tuned for 111 Bragg reflection is shown in Fig. 2. Note that, when a proper mirror coating is used, the maximum heat flux on the first crystal is less than about 2.3 W/mm^2.

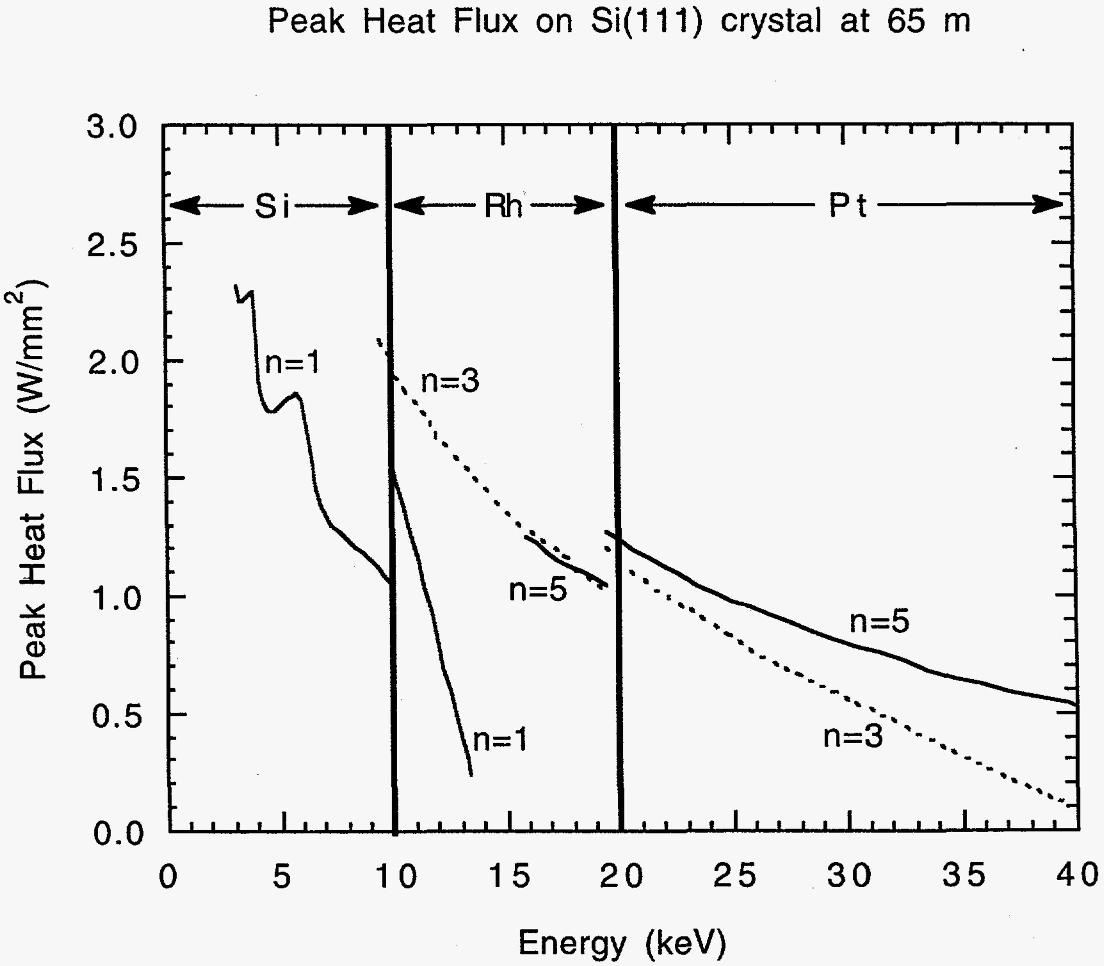

Fig. 2 Peak heat flux on the surface of a Si(111) crystal located at 65 m from Undulator A. The Si crystal is tuned to diffract the energy labeled along the axis, which can be obtained from the first, third, and fifth harmonics of the undulator. It is also assumed that the Si mirror will be used to cover an x-ray energy range of 0-10 keV, the Rh and Pt mirrors to cover the 10-20 keV and 20-40 keV energy ranges, respectively. The grazing angle of incidence on the mirror is 0.15°.

For a peak heat flux of 5W/mm^2 and a total power of 600W, we have designed a water-cooled first crystal with less than 2 microradians of tangential slope error over the footprint of the FWHM of the undulator radiation. A schematic of such a design is shown in Fig. 3. The main design feature is that the reflecting surface is a virtual symmetry plane in terms of the thermal and mechanical properties of the crystal. In other words, the bending moment produced by the incident beam in section B is thermally and mechanically balanced by the reverse bending moments in sections, which can be obtained by properly selecting the shape of the crystal and the cooling geometry. Because the reflecting surface is a virtual symmetry plane, the thermally induced slope error of the reflecting surface should be independent of the peak heat flux and the total power to first order of approximation. The maximum temperature in the crystal, however, will increase with the total power and the peak heat flux.

The design uses a monolithic piece of crystal and only simple machining is required. This fact combined with the water cooling makes this design a very attractive solution for handling the high heat load for APS undulator radiation in terms of cost and maintenance. It is worthwhile to note, however, that the new crystal design has not yet been evaluated experimentally.

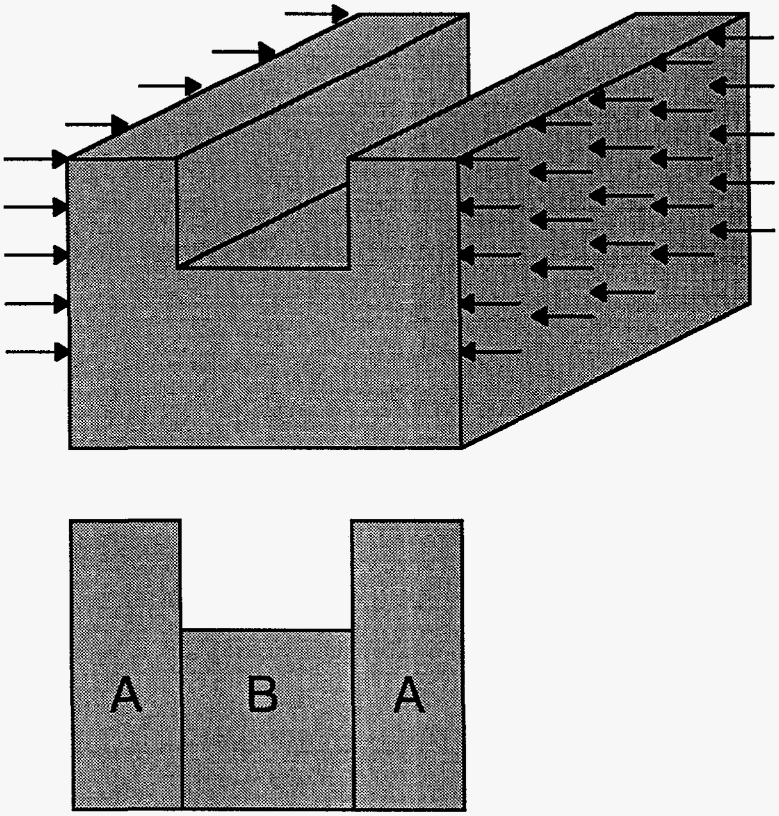

Fig. 3 A schematic of a thermally and mechanically balanced crystal design for high-heat-load applications. The main design feature is that the reflecting surface is a virtual symmetry plane from the thermal and mechanical point of view. The

incident beam is assumed to be incident on the central bottom part of the U shape of the crystal, i.e., the central top part of the B section.

The energy tuning of the double-crystal monochromator is commenced by rotating the two parallel crystals using a single actuator. The surface of the first crystal is aligned with the rotation center to ensure that the center of the incident x-ray beam footprint on the crystal surface does not change with rotation and the diffracted x-ray energy. The off set between the diffracted and incident x-ray beams will be set to about 1 cm. The selection of this small off set enables one to scan the DCM over a reasonable x-ray energy range with negligible position displacement in the diffracted beam. The possibility of using this small off-set is partly because the bremsstrahlung radiation is separated from the synchrotron beam by the M1 mirror. In order to keep the direction of the diffracted beam stable with x-ray energy change, it is important to keep the temperature difference between the two crystals to less than about 15 C°.

For double-multilayer monochromators, small incidence angles are used and thus the heat flux incident on the first multilayer can be significantly reduced. For a 2 degree incidence angle, the incident heat flux is reduced to about 0.4 W/mm^2. Multilayers that are able to take this level of heat flux have been demonstrated by several groups.[9]

II.8 Aperture/Beam Position & Io Monitor Unit

A multifunctional unit downstream of the DCM is used for the following: (1) an accurate adjustable aperture; (2) beam position monitor; and (3) monitor of flux (I_0) of the beam monochromatized by the DCM or DMM. These functions are to be carried out for either the monochromatic or the pink beams. The unit consists of four independent, movable blades and can be translated with 1 µm accuracy. The blades will be water cooled. Signals of total electron yield from each of the four blades will be used for both beam position and Io monitoring.

II.9 Pink Beam Shutter

In addition to the front-end white-beam shutter, the beamline has two additional pink-beam shutters. The first pink-beam shutter is downstream of the mirror but upstream of the monochromators. This shutter is designed to prevent the pink beam from propagating down the beamline while keeping the mirror illuminated by radiation. This shutter is closed when the other two branchlines are in operation. The pink-beam shutter downstream of the monochromators is used to control access to the experimental stations or exposure to a sample.

II.10 Experiment Station

A scanning x-ray microprobe and an imaging microscope will be developed as the major x-ray instrumentation in the experimental station. The focusing optic for the scanning microprobe will be either a phase zone plate or an elliptical mirror. A focal spot approaching 0.1 μm may be expected. The scanning microprobe will be used for applications including spatially resolved x-ray microspectroscopy, differential absorption contrast microscopy, microdiffraction, and microanalysis. An image is formed by raster scanning of a sample across the focus of the focused beam. The imaging microscope will be used for three-dimensional computed tomography.

A position-sensitive CCD detector will be available for spatially resolved microdiffraction and imaging microscope applications. A 13-element Ge energy-dispersive detector will be used to increase the count rate for fluorescence analysis. A wavelength-dispersive spectrometer will be procured for high-energy-resolution analysis of fluorescence signals.

III Conclusion and Discussion

The design of the 2-ID-D/E beamline, which is dedicated to the development of x-ray microfocusing- and coherence-based techniques and applications, and the major beamline optical components are described. The beamline layout and the component specifications were made to achieve the spectral and coherence properties required by the scientific programs. The-high-heat-load problems encountered in undulator beamlines at the APS are solved by using a fixed aperture to remove the power outside of the undulator central cone, using a mirror to filter out the power of high energy x-rays, and using innovative cooling designs of the high-heat-load optics. In our design, all optical components are cooled by water.

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