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Present and Future Optics Challenges at CHESS and for Proposed Energy Recovery Linac Source of Synchrotron Radiation

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ABSTRACT

We present recent test results and discuss design challenges on x-ray optical components for the wiggler sources at CHESS and for the proposed energy recovery linac (ERL) source at Cornell. For the existing wiggler sources, a new white-beam collimating mirror has been installed and tested at F-line and some preliminary test results are presented. For the proposed ERL, three types of x-ray optical components are identified and considered: (1) high-heat-load capable optics for high-power and high-power-density insertion-device sources, (2) brilliance preserving optics that can provide high transverse coherence, and (3) optics used to manipulate, preserve and produce short x-ray pulses.

Keywords: high heat load, x-ray optics, energy-recovery linac, high brilliance

1. INTRODUCTION

As one of the pioneer synchrotron radiation laboratories that was built more than twenty years ago, Cornell High Energy Synchrotron Source (CHESS) has played a significant role in the development of x-ray optics. This is especially true in the area of high heat load and high x-ray flux optics [1-5] since the high critical-energy wigglers at CHESS are among the most powerful insertion devices in the synchrotron world [6] partly due to the increased beam currents in the Cornell Electron Storage Ring (CESR). At present conditions, 5.3 GeV and 380 mA, each 24 pole wiggler at A- and F-lines produces about 22 kW of power in 4 mrad opening angle with a critical energy of 22 keV. These high total power devices represent a very different challenge in x-ray optics designs as compared to the 3rd generation undulator sources.

In the mean time, a completely new type of synchrotron radiation source is being proposed at CHESS in collaboration with Laboratory of Nuclear Studies at Cornell University and with physicists at Jefferson National Laboratory [7-10]. The new source is an energy-recovery linear accelerator (ERL) driven, undulator-based synchrotron source that has the potential to provide many advantages as compared to the present storage-ring based facilities. Two distinct advantages of the ERL are (a) high coherence in both transverse dimensions (small source sizes) and (b) short x-ray pulses on the order of 100 femtoseconds. These two properties of the ERL present new challenges to x-ray optics design and fabrication in addition to the heat load challenges that already exist at the third generation synchrotron sources.

In this article, we review recent high-heat-load optics improvements at CHESS wiggler beam lines and discuss future optics challenges that the ERL would bring.

2. IMPROVED OPTICS FOR WIGGLERS

With the continued increase in CESR current, the front-end x-ray optics at A- and F- wiggler lines at CHESS require considerable redesign and improvements. The F-line front-end has now been completely rebuilt, and the A-line rebuild is current underway. Major improvements at F-line include a redesigned

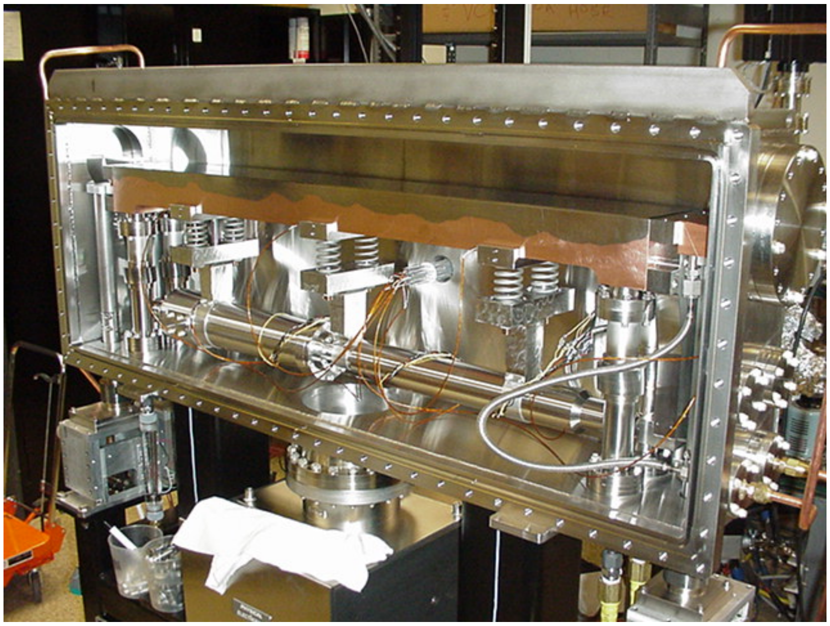

Figure 1. CHESS F-line white-beam mirror in its ultra-high-vacuum vessel. It consists of a flat Glidcop substrate with rhodium coating, a variable-force U-bender, and a system of springs for gravity compensation.

energy-tunable monochromator for multiple-wavelength anomalous diffraction (MAD) experiments at F2 station, and a new water-cooled white-beam mirror (Fig.1) installed as the first optical element. The improved F2 monochromator has been discussed in a previous publication [5], and in this article we focus our attention on new test results obtained after the installation of the white-beam mirror.

The white-beam mirror was designed and fabricated by Societe Europeenne de Systemes Optiques (SESO), and consists of a flat bendable 1 m long Glidcop substrate coated with rhodium, a variable-force mirror-bender, and a gravity compensation mechanism [11]. The mirror vacuum box was designed in house at CHESS and fabricated by Kurt Lesker.

The white-beam mirror serves two crucial functions. First, it operates as a power filter so that the heat loads at F1 and F2 monochromator crystals are reduced by more than two-thirds as shown in Figure 2. Second, the mirror can be vertically bent to collimate the x-ray beam and make it more parallel, increasing the energy resolution for MAD experiments at the F2 station without significant loss of x-ray flux. Shown in Figure 3 is an example of several energy scans with a pure Se foil around the Se K absorption edge, as a function of the mirror bend (in stepper pulses). The sharpening of the white line in the spectrum indicates an increase in energy resolution as expected.

The redesigned new F-line also employs separate ultra-high-vacuum compatible mono-

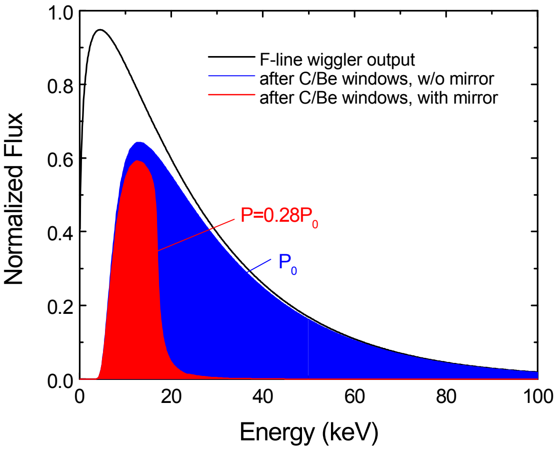

Figure 2. Calculated comparison of F-line wiggler outputs with and without the installation of the white-beam collimating mirror, showing a reduction of power P_0 by more than a factor of three.

chromator and mirror enclosures to reduce thermal cross-talks among crucial optical components. These improvements, together with the reduction of high energy photons due to the installation of the white beam mirror, have resulted in more stable x-ray beams into F1 and F2 experimental stations. For example, thermal drifts on downstream optical components are dramatically reduced. Shown in Fig.4 is a comparison of the changes, during a normal beam fill, in the required piezoelectric transducer control voltage used to keep the F2 double crystal parallel. It can seen that reduction in voltage correction is about a factor of five (normalized to beam currents), resulting in a more stable beam and more reproducible beam energy for MAD experiments.

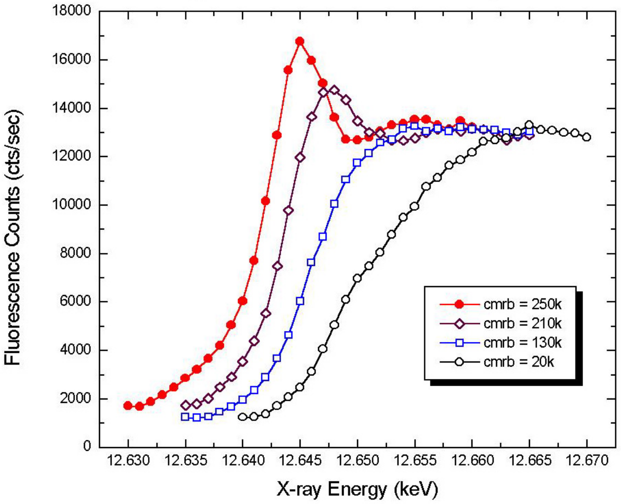

Figure 3. Energy scans around the Se K-edge at different bender settings 'cmrb' for the collimating mirror, upstream of the double crystal monochromator at F2 station. A higher numbers indicate a smaller bending radius. The shift in the edge position indicates a slight change in the deflection angle of the mirror when its bend is changed.

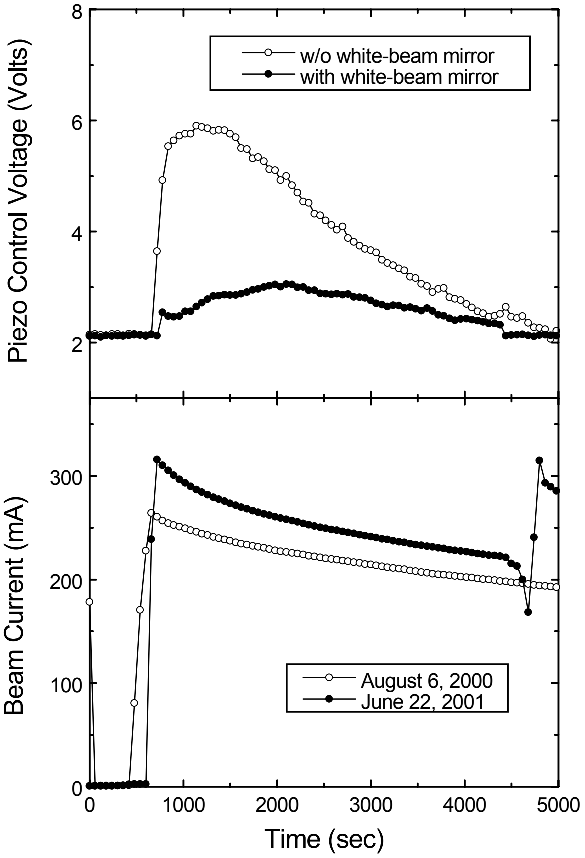

Figure 4. Top panel shows a comparison, before and after the installation of the F-line white-beam mirror, of the changes in the control voltage during a normal fill to a piezo transducer in order to keep the two monochromator crystals parallel for the F2 station. Vertical scale corresponds to 1 volt = 5.4 arc-seconds. Bottom panel shows the beam currents during the same time intervals as in the top.

3. PROPOSED ERL SOURCE

The new energy recovery linac (ERL) synchrotron radiation source proposed at Cornell is based on closed-loop energy recovery with superconducting linear accelerators and small-gap short-period undulators [7-10]. It offers significant advantages over storage ring sources, both in terms of the possible x-ray beams and, once the technology is developed, cost-effectiveness. The basic idea behind an ERL was suggested long ago for beam colliding machines [12] and the feasibility of operating an ERL has recently been demonstrated with a highly successful free electron laser at Jefferson Laboratory [13].

Table 1: Preliminary design parameters for the Cornell ERL source.

High duty-cycle operations		ERL high-flux	ERL high-coherence
Machine design	Energy E_G (GeV)	5.3	5.3
	Current I (mA)	100	10
	Charge q (nC/bunch)	0.077	0.008
	ε_x (nm-rad)	0.15	0.015
	ε_y (nm-rad)	0.15	0.015
	Bunch fwhm τ (ps)	0.3 – 5	0.3 – 5
	# of bunches f (Hz)	$1.3\cdot10^{9}$	$1.3\cdot10^{9}$
Insertion device	Undulator L (m)	25	25
	Period λ_u (cm)	1.7	1.7
	# of period N_u	1470	1470
	Horizontal β_x (m)	12.5	4.0
	Vertical β_y (m)	12.5	4.0
	Undulator K @ E_1	1.38	1.38
	1st harmonic E_1 (keV)	8.0	8.0
Beamline & optics	H. div. fwhm (μrad)	9.1	6.2
	V. div. fwhm (μrad)	9.1	6.2
	H. source fwhm (μm)	103	24.5
	V. source fwhm (μm)	103	24.5
	Power P_0 (kW)	33.9	3.4
	dP/dA @20m (W/mm^2)	2600	260
Basic properties	Ave. flux F_n (p/s/0.1%)	$1.5\cdot10^{16}$	$1.5\cdot10^{15}$
	Ave. brilliance B (p/s/0.1%/mm^2/mr^2)	$1.3\cdot10^{22}$	$5.2\cdot10^{22}$
	Photons / bunch	$1.2\cdot10^{7}$	$1.2\cdot10^{6}$
	Peak brilliance (p/s/0.1%/mm^2/mr^2)	$3.0\cdot10^{25}$	$1.2\cdot10^{26}$
	Peak flux (p/s/0.1%)	$3.9\cdot10^{19}$	$3.9\cdot10^{18}$

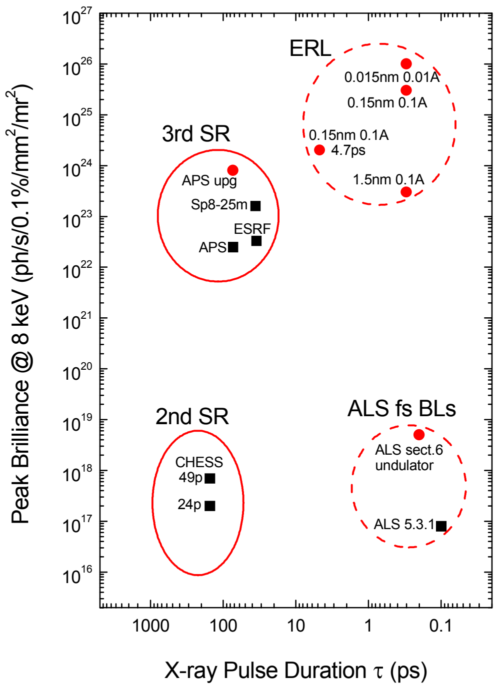

Figure 5. Peak brilliance vs pulse length of various synchrotron radiation sources. It shows that the proposed ERL source would push fast timing experiments into new territories. The ERL numbers illustrate possible values for emittances, beam currents, and full pulse lengths. CHESS 49/24-pole wigglers numbers represent typical values for second generation storage-ring sources.

The basic machine parameters for the proposed Cornell ERL are listed in Table 1. As can be seen from Table 1, the ERL would produce round synchrotron x-ray beams with average brilliance more than one order of magnitude higher than the existing storage rings, making the ERL comparable in this regard to proposed prototype 4th generation x-ray free-electron laser (XFEL) sources [14,15]. In its high-duty-cycle mode the ERL would provide two-to-three-orders-of-magnitude higher peak brilliance than existing sources by providing ultra-short x-ray pulses. Furthermore, in the regime of short pulses the ERL could produce more than five orders of magnitude increase in peak brilliance (Figure 5) as compared to the existing and proposed short-pulse sources. Even with the 4th generation prototype sources to be developed, for certain scientific applications such as nonlinear x-ray photon interactions with matter (see Figure 6), the ERL would enable new studies in currently unattainable regimes and would allow experimentation using repeated pulses rather than single-shot measurement.

In order to realize the outstanding potentials of an ERL source, three challenges in x-ray optics developments would have to be met: (1) handling high heat loads, (2) preserving brilliance for high transverse coherence beams, and (3) preserving and manipulating fs x-ray pulses. In the following section, we briefly discuss each of these areas.

4. OPTICS CHALLENGES FOR THE ERL

Heat load tolerant optics design

The concerns about heat loads on the x-ray optics are also concerns for the existing 3rd generation machines and, certainly, for the planned 4th generation XFEL machines. Table 2 gives a comparison of heat loads expected from the ERL and from undulators now installed at SPring-8, both at 8 keV.

Table 2: Comparison of heat loads at Cornell ERL and SPring-8

	ERL undulator @ 5.3GeV		SPring-8 undulator @ 8 GeV	
ID length	25 m	25 m	25 m	4.5 m
Beam current	100 mA	10 mA	100 mA	100 mA
Total power	33.9 kW	3.4 kW	31.2 kW	15.7 kW
Power/Area @ 20m	2600 W/mm^2	260 W/mm^2	4568 W/mm^2	1830 W/mm^2

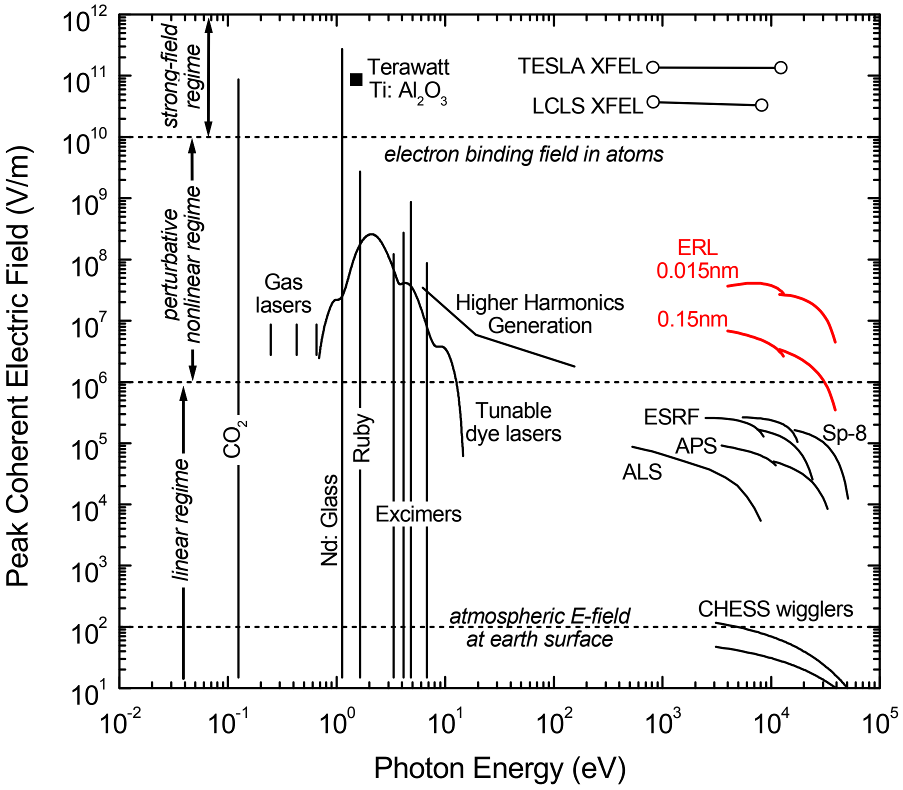

Figure 6. Peak coherent electric field strength vs. photon energy of various radiation sources, showing the possibility that the Phase II ERL will open up a new area for nonlinear optical research even with the XFEL projections. Different regimes of nonlinear photon-matter interactions are based on knowledge of nonlinear laser materials in the visible region [15]. Laser sources are from [16,17].

Based on the time-averaged power and heat load tolerance, optics designs that work successfully at SPring8 should also work at the proposed ERL. At present, published reports [19,20] are available on the performance of the SPring8 standard high heat load (asymmetric-inclined) crystal monochromator and 4.5 meter undulator, where measurements indicate a specific flux of $5x10^{10}$ photons/second/mm^2 at 10 keV and 1 km from the source. This is about 25% of the flux expected for perfect optics. Assuming that the deviation is due to heat loading implies that the heat load issue is far from completely solved and challenges remain for the proposed ERL.

One should also consider non-thermal effects on optics associated with instantaneous power and peak electric field. Mills [21] has examined such concerns by comparing expected pulse width and fluence from XFEL sources to results obtained in studies of lattice damage in short-pulse laser experiments. The prototype XFEL source being proposed at Stanford is predicted to produce $2x10^{12}$ photons at 8 keV per 230 fs pulse. Given the source parameters, this corresponds to a fluence of 40.3 Joules/cm^2 at 50 meters. After factoring in x-ray absorption, Mills concludes that non-thermal damage should not occur in diamond optics and may not occur for silicon. In comparison, the ERL would produce 300 fs pulses with a fluence at 50 meters of 7.2(1.6) $x10^{-6}$ Joules/cm^2 in high flux (high coherence) mode. This much lower value is however not the whole story since Mills considered pulses from the XFEL operating at 120Hz, while the ERL duty cycle is planned to be higher by 10^{7}. However, if non-thermal damage can be ignored, then we need consider only thermal (equilibrium) effects of power and then it is safe to return to our comparison with SPring-8.

We are unaware of published reports on the optical performance of components on the SPring-8 25 meter undulator beam line. This is not surprising, since this undulator only recently went into operation.

We believe that the magnitude of the problem will become clearer after more operating experience is gained with this device.

Preserving x-ray beam brilliance and transverse coherence

Transverse coherence is preserved by eliminating the distortion of the wave-front in passing through beamline components, such as x-ray windows, monochromators, and focusing devices (mirrors, refractive lenses, phase plates, etc.). An upper bound on wave-front distortion can be estimated by reference to beam characteristics for the ERL listed in Table 1.

In high coherence mode the proposed ERL beam spot size at 50 meters is dominated by the angular size of the source. If portions of this beam deviate in angle, the spot size will enlarge. For instance, an average slope error on reflecting surfaces of 3 μrad should add angular size, in quadrature, enlarging the beam from 311 to 440 microns. State-of-the-art slope errors (rms) in mirror manufacture stand at or below 2 μrad [22]; however, thermal distortions can cause considerably larger slope variation.

A second, closely related criterion for perfection of x-ray optics involves preserving transverse coherence. The source size and wavelength together define an angle within which the wave-front has a well-defined phase (points on the wave-front have a definite phase relation). At 8 keV for the ERL this angle is 5.3 μrad, so distortions on this order will render the beam incoherent.

Table 3 shows that the horizontal source properties of the ERL in high coherence (10mA) mode result in a beam smaller than storage ring sources, and comparable to the XFEL. In contrast to these sources, horizontally flattened storage ring sources require that for maximum brilliance the optics operate in vertical scattering geometry. The ERL can have a round electron beam which allows the undulator and/or scattering plane for the optics to be rotated by any angle about the beam direction without loss of brilliance. (Polarization factors alter this slightly.) Assuming beam divergence orthogonal to the scattering plane is preserved through optics, then brilliance preserving optics for SPring8 with the 25m undulator should also work at the ERL. In another word, based on source phase space, the level of perfection (in terms of slope errors) for the ERL optics is comparable to that for the SPring8.

Table 3: Comparison of transverse coherent properties of the ERL and some other sources

		25m ERL undulator 5.3 GeV		SPring8 8 GeV	ESRF 6 GeV	LCLS XFEL 15 GeV
Operation / Undulator length		100 mA	10 mA	25 m	5 m	100 m
Source size (μm)	horizontal	103	24.5	890	879	78
	vertical	103	24.5	22.8	13.9	78
Source div. (μrad)	horizontal	9.1	6.2	37.4	26.8	1
	vertical	9.1	6.2	4.3	10.4	1
Beam size (μm) @50m	horizontal	467	311	2071	1603	93
	vertical	467	311	216	520	93
Average brilliance (p/s/0.1%bw/mm^2/mrad^2)		1.3x10^{22}	5.2x10^{22}	2.2x10^{21}	3.1x10^{20}	4.2x10^{22}
% beam coherence		0.52	20	0.14	0.14	100

Early results from measurements at the SPring-8 1 km long beamline BL29XU give a practical indication that transverse coherence can be preserved through beamline optics. First reports on diffraction enhanced imaging and topography [19] illustrate the following facts. First, problems with storage ring stability affect these measurements, and second, if monochromatic images are taken through a fast shutter (to abrogate beam motion) excellent phase contrast is visible over an area as large as 10 mm by 10 mm. This implies that the x-ray beam coherence can be preserved through the x-ray optics.

The most challenging issues in preserving brilliance in x-ray optics are found in micro-beam applications, which could potentially benefit significantly by the ultra-low emittance in the ERL. Using a 2m long undulator with a 1m beta function in a 0.015 nm-rad ERL machine, it would be possible to obtain an electron beam size $\sigma_x = \sigma_y = 3.9$ μm in both directions. In order to take full advantage of this small source size using a focusing optic, the required slope error δ would have to be (much) smaller than the ratio of σ_x to the distance D from the source to the optic. If D = 20 m, then $\delta < \sigma_x / D = 0.2$ μrad, which is an order of magnitude more stringent than what the current state-of-the-art optics can provide.

Challenges associated with the ERL temporal properties

Because an ERL can provide x-ray pulses two to three orders of magnitude shorter than those from existing storage rings, we face several new challenges in x-ray optics. First, we would like to know whether x-ray optics can preserve the temporal properties of the ERL beams. Second, we would like to know whether very short pulses affect the throughput of optics. Finally, we would like to investigate whether special optics can help making short x-ray pulses.

One of the fundamental principles that governs the x-ray optics for short pulses is the relation between pulse length and Bragg reflectivity. When the x-ray pulse length (in space) is smaller than the extinction length in a perfect crystal (or the absorption length in mosaic crystals) simulations by Wark [23] predict that integrated reflectivity will be reduced from conventional values. This effect, if true, would be very significant for mosaic crystal optics and for perfect crystal near-back reflection analyzers used in high resolution inelastic scattering. A 300 fs pulse from the ERL is about 90 micron long and this may be compared to perfect crystal extinction lengths that range from 5 to 100 microns. The pulse is measured along the incidence beam direction while extinction is measured normal to the Bragg planes, so reflectivity reduction may be sensitive to angle of incidence.

This effect can be thought of as a response time of the crystal to x-rays. It is being studied as a means to filter out extremely short fluctuations in source intensity, but may ultimately limit the delivery of short pulses [24]. For a practical set of silicon (111) optics, Shastri and Mills [24] calculated the added temporal spread to be less than 5 fs. For higher order reflections and narrower energy bandwidths, this number can stretch out to many 10s of femtoseconds. The situation for mosaic crystals can be much worse because reflectivity is limited by absorption in the material.

Another issue that will need to be addressed when optimizing x-ray optics for short pulse beams concerns the distortion, in space and time, of pulse shape in the process of scattering [25]. If a beam wavefront is not specularly reflected by an x-ray optic, then the shape of the front (and pulse) emerges from the reflection having suffered a linear transformation (mixing of position and time) in shape. This will tend to broaden the time width of pulses and would be particularly significant when time resolution is paramount and for optics such as asymmetric-inclined crystal monochromators and zone plates.

On the other hand, when designed properly and used in conjunction with novel accelerator devices, the linear transformation in space and time mentioned above can be taken advantage of to help producing short x-ray pulses. For example, by tilting an electron bunch in the longitudinal and the vertical directions in an x-ray undulator, Zholents et al. [26] have proposed to use asymmetric optics to compensate for the electron bunch tilt, producing shorter, longitudinally compressed x-ray pulses.

Issues pertaining to the x-ray optical effects of very short x-ray pulses are an area of great current interest for which the community at large has very little experience. It will begin to be explored in the next few years by the appearance of ways of generating fast (if relatively low intensity) x-ray pulses [27] and by the R&D efforts of the XFEL activities [14,15] as well as other proposed ERL-type machines [28,29]. We plan to be involved in these new developments and to collaborate with colleagues doing experimental work at other facilities in order to gain expertise in this emerging area.

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