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OPTICAL CAVITY VS. ELECTRON BEAM REQUIREMENTS FOR THE OPERATION OF A 1.5 Å LCLS IN A REGENERATIVE AMPLIFIER MODE*

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Extended Abstract

In current designs for 100-1 Å Linac Coherent Light Sources (LCLSs), i.e., single-pass gain-saturating FELs [1], a major cost component is the undulator. If the mode of operation could be switched to that of an oscillator (or, more appropriately, regenerative amplifier), substantial size and cost savings could be realized. Unfortunately, simple cavities based on normal-incidence specular or multilayer optics cannot be realized straightforwardly in this spectral regime. In prior work, e.g., the use of diffracting crystal resonators was discussed [2], but the operation of such a cavity is tied to a single frequency, negating one of the main advantages of the FEL. A broad-band multi-facet ring cavity operating at grazing incidence has been proposed, fabricated, and tested at LANL [3] for operation down to 1000 Å, but the extension of this scheme down to substantially shorter wavelengths has not as yet been pursued. The basic requirements necessary for progress in this direction can be associated with four areas: 1) specular or interference-based reflectivity, viz., the optical and lattice constants of materials and material systems; 2) optical scattering, viz., the surface quality of materials and interfacial quality of material systems; 3) peak power fundamental and harmonic damage effects; and 4) electron/photon pulse synchronization. Of these, perhaps the most demanding in terms of current technology is synchronization. For example, efficient

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operation of a 1.5Å LCLS amplifier would require repetitive pulse-to-pulse synchronization of 160 fs long bunches to better than a 50% transverse and longitudinal overlap, but , e.g., the temporal jitter currently cited for electron bunches at SLAC and elsewhere is ~0.5ps [4].

The basis for this note is that in cavity operation of a high-gain amplifier vs. a low-gain oscillator, a substantial reduction in the reflectivity R of the optical elements, or alternatively, in the total cavity transmittance, T_T, can be considered. The optimization of reflectivity in this case is concerned with providing sufficient net gain so that a reasonably fast buildup of gain saturation can be achieved. For an undulator of sufficient length, this allows a wide range of materials (notwithstanding the fact that all are absorbers in the x-ray range) and optical elements (mirrors, multilayers, and crystals) constructed out of them to be employed. Selected research and development (r&d) issues associated with these possibilities, as well as with the underlying areas referred to above, are briefly described in this abstract.

In recent investigations at SSRL, the performance of a number of optical elements and possible FEL cavity configurations was analyzed using a comprehensive data base of optical constants (δ and k, where ((1-δ)+ik) is the complex index of refraction [5]) spanning the 1000Å-1Å range. These included: 1) specular reflectors, 2) multilayers, 3) multilayer etalons [6], and 4) crystals. Selected results, neglecting the effects of specular surface scattering, are summarized in Table 1. To illustrate the principle of cavity operation, we can refer to Fig. 1. The basic configuration, utilized for the LCLS take-off mirror scheme, is a sequence of multiple reflections at extreme grazing incidence angles θ_i (Fig. 1, top). The total angular deviation , θ_T, is equal to θ_i times twice the number of reflecting surfaces. Thus, assuming all surfaces are tangent to a circular contour, to turn the beam back by 2π radians would require π / θ_i reflections. If all the facets are planar, the total length ℓ of each facet is determined by the diameter D_W of the light beam divided by θ_i. Due to the high values of γ (the Lorentz contraction factor) in the Å-range LCLS, D_W is typically small (<50μ), so that even at very low grazing incidence angles, the required lengths of the reflecting facets are relatively small. In initial design studies of this system at 40Å [7,8], a basic focus was on the parameter R, the reflectivity of a single facet, and the general trend, for $\theta_i > \theta_c (\equiv \sqrt{2\delta})$, revealed the expected increase of R vs. Z, the atomic number of the reflecting material. Prompted by an analytical approximation to

R for $\theta_i < \theta_c$, viz., $R \cong 1 - 2(k/\delta)\cdot\left(\theta_i/\sqrt{2\delta - \theta_i^2}\right) + \ldots$, a subsequent search also established that the ratio (k/δ) is very strongly minimized for the low-Z elements. The theoretical performance of the lowest-Z materials was, in fact, found to be good enough for the implementation of a ring cavity to be considered. In the present context, this is a simple extrapolation of the top scheme in Fig. 1 to reflect the beam around by 2π radians. For a very large number of reflections, the facets will approximate to a continuous surface (Fig. 1, bottom). The effect of the total single-pass transmittance T_T of such a ring cavity on the required length of the undulator can be estimated by requiring the single-pass gain of the undulator to be greater than $(T_T)^{-1}$. Using basic FEL theory [9], this can then be converted into the required number of undulator gain lengths by the expression $L_{sat}\cdot(\ln(T_T)/22)$, where L_{sat} is the LCLS undulator saturation length. In Table 2, selected performance and design parameters of circular cavities constructed out of Gold, Nickel, Carbon, and Beryllium are shown for 1.5 Å FEL operation.

For wavelengths larger than 30Å, multilayer or multilayer etalon optics would appear to offer acceptable performance for normal or near-normal incidence resonators [10]. This wavelength is determined from: 1) the multilayer period, or d-spacing, for which the relation λ=2d holds; and 2) currently attainable values of interfacial roughness (~2-4Å), which must be kept substantially smaller than the d-spacing for acceptable performance to be attained. While further development should extend the use of normal-incidence multilayer optics to even shorter wavelengths, the major problem for normal-incidence LCLS applications is expected to be peak power damage [7,11]. To this end, it is in principle possible to consider designs based on grazing-incidence beam expanders to mitigate damage effects (see Fig. 2). To extend the wavelength range of multilayer resonators further, both with respect to peak power damage and reflectivity R, grazing-incidence multi-facet cavity operation using single or etalon multilayers can be considered. In Table 3, multi-facet (Fig. 1, top) cavity parameters are shown for angles of incidence ranging from 2°-6° and assumed reflectivities of 90%. The indicated parameter ranges are, in practical terms, extremely demanding, and whether or not they can be approached with realizable multilayer structures and material systems at the assumed wavelengths remains to be seen.

The theoretical focus of continuing r&d on x-ray optical cavities should include: 1) the optimization of cavity shapes given an undulator of definite length; 2) ray tracing and analytical assessment of light pulse propagation through cavities 3) assessment of different cavity cross sectional shapes and the effect of distributed vacuum pumping apertures on the transmittance; 4) transverse/longitudinal beam dilation and tolerances; and 5) simulation and assessment of the effects of scattering and radiation damage in different cavity geometries. Experimental r&d activities should include: 1) the investigation of methods for preparing ultra-smooth high-Z and low-Z (e.g., B or diamond [12]) material surfaces; 2) development of high-performance multilayers and multilayer etalons; and 3) the characterization of performance (in particular light scattering vs. surface roughness) and damage effects on available SR beam lines. An interesting technique, made possible by the time structure of the class of FEL considered here is the use of dynamical optics to extract the beam from the resonator [7]. As mentioned above, significant progress in the control of electron beam stability will be required before full resonators on linac-based LCLSs becomes possible. If, for example, we assume that the photon and electron bunches should overlap, repeatably, by >50% in both longitudinal and transverse directions, a 1-2 order of magnitude improvement in transverse and longitudinal beam jitter control in comparison to present levels will be required. At the same time, if ring cavities can be successfully deployed, this may enable the development of x-ray FELs on linacs or alternative sources with substantially longer (and temporally more stable) bunches, making the systematic investigation of the optics issues discussed here an iteratively rewarding r&d activity.

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Tables

Table 1. Optical elements and applicable wavelength ranges for X-ray FEL resonators.

REFLECTOR	**Large Angle**[a] ($\theta_i \le \pi/2$)	**Grazing Incidence**[b] ($\theta_c < \theta_i << \pi/2$)	**Extreme Grazing**[c] **Incidence** ($\theta_i < \theta_c$)
Specular[d]	-	>100nm	<10nm
Multilayer[e]	>3nm	>2nm	-
Multilayer Etalon[e]	>1-2nm	>1nm	-
Crystal (Bragg)[f]	<1nm	<1nm	-

[a]Normal or large-angle incidence: 2-16 reflectors.
[b]$\ge$16 reflectors.
[c]Continuous-surface, or capillary.
[d]Broadband (ideal surfaces assumed).
[e]Narrow to medium band (BW >1/N).Assumed interfacial roughness in the 2-4Å range.
[f]Fixed narrowband (BW<1/N).

Table 2. Ring cavity parameters for a 1.5 Å FEL oscillator for 4 different elements. D_W=50m.

	Au	**Ni**	**C**	**Be**
θ_c[mr], k/δ	12.1, 0.099	8.82, 0.02	4.8, 0.0015	3.9, 0.001
θ_i[mr]	0.8	0.8	0.8	1.6
# of bounces	3927	3927	3927	1964
T_T	6.7x10^{-23}	4.24x10^{-7}	.133	.175
ln(T_T)/22	>1	0.66	0.092	0.079
ℓ [cm]	6.25	6.25	6.25	3.125
Ring Perimeter [m]	245.4	245.4	245.4	61.4

Table 3. Parameter requirements for 1.5 Å multi-facet ring cavities using facets with 90% reflectivities. D_W=50m.

θ_i **[r]**	**# of reflections**	T_T	**d [Å]***
0.034	93	5.55x10^{-5}	21.5
0.068	47	7.010^{-3}	10.75
0.102	31	3.8x10^{-2}	7.18

*Period (d-spacing) required for multilayer facets.

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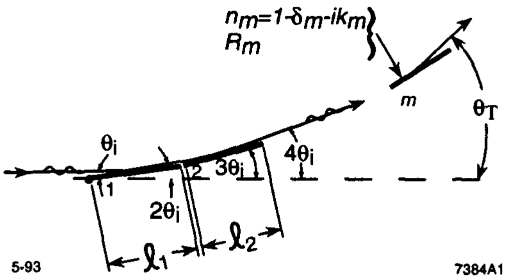
Figure Captions

Figure. 1 . Grazing-incidence geometry of the LCLS (left) and extension of the scheme to a continuously-curved ring cavity (right).

Figure. 2. Schematized normal-incidence X-ray FEL resonator based on multilayer optics. An expander/collimator geometry is utilized to minimize peak power damage.


$n_m=1-\delta_m-ik_m$
R_m
m
θ_T
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1
2
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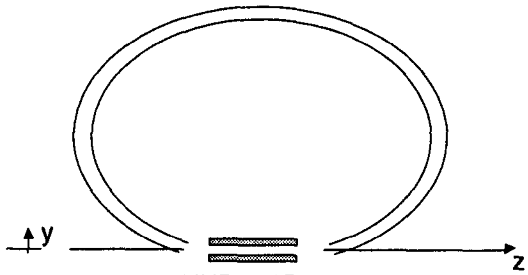
LOW-Z X-RAY CAVITY
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LCLS NORMAL-INCIDENCE CAVITY (λ>3nm)