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**Designs for Optical Components
Related to the Los Alamos Free-Electron Laser ***

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ABSTRACT

Several optomechanical tasks for the Los Alamos National Laboratory's (LANL) Free-Electron Laser (FEL)^{1,2} were set by the envisioned project goals as early as 1988. Unfortunately, the FEL project has been set aside due to funding constraints. The tasks reported on here required extensive modeling for final adaptability into the FEL environment. The systems to be described are best identified as 1) a Brewster attenuation device, 2) an optical mode relay lens system, 3) a spectral harmonics band-filtering system, 4) a 25-nm micropulse spectrometer system, 5) a 12.5-nm micropulse spectrometer system, 6) a 0.6-nm micropulse spectrometer system, and 7) a reflective mode profile rotator. The Brewster attenuation device was successfully used inside the FEL resonator. The optical mode relay lens system, spectral harmonics band filtering system, and reflective mode profile rotator were completed but never used. The 25-nm micropulse spectrometer was optically and mechanically completed, but the detector electronics were never finished. The 12.5- and 0.6-nm micropulse spectrometers were never assembled, due to hardware that was common to the 25-nm system.

These systems will be described in the order listed above. The nominal wavelength of operation for the listed systems is 3.0 μm , except for the harmonics filtering which works on the subharmonics of 3.0 μm . All of these systems were operated remotely due to the harsh radioactive/x-ray environment during FEL operation. The FEL resonator, optical diagnostic path, and amplifier path are shown in Fig. 1.

1. BREWSTER ATTENUATION DEVICE

The Brewster angle can be utilized in this device in that the FEL has a highly polarized output, even within the cavity where this device was designed to be used. Since the FEL electrons are undulated in one axis only, the magnetic perturbations due to small errors in the undulator system are the only contributors to polarizations other than the primary axis. Output power can be minimized by orienting a Brewster plate such that the polarization vector is parallel to its surface and the tilt of the plate satisfies the condition

$$R_t = [\tan(\theta_i - \theta_t)]^2 / [\tan(\theta_i + \theta_t)]^2, \quad (1)$$

where θ_i and θ_t are the incident and transmitted angles of the beam with respect to the normal to the surface.³ The transmitted angle θ_t can be calculated using Snell's law

$$\theta_t = \sin^{-1}[\sin(\theta_i)/n], \quad (2)$$

where n is the refractive index of the plate material, in this case CaF₂. The index of CaF₂ at 3.0- μm wavelength is 1.417852, making the Brewster angle 54.805°.

The minimized transmission of this device, when near the Brewster angle, was of value in order to evaluate the absolute losses within the FEL cavity. (The FEL would have no gain if the internal cavity losses were higher than the gain afforded by the regenerative path of photons through the electron undulator.) The device was also of value in studying the turn-on characteristics of the FEL in the event that the gains were just slightly higher than the losses. The nominal configuration of the LANL FEL provided very high gains within the cavity, thus not allowing this evaluation without having to tailor multi-layer dielectric coatings on the resonator mirrors for each gain value to be studied. The cost in time and dollars for this approach led us to the Brewster plate device. Analysis in CodeV and the LANL FEL code FELEX showed minimal degradation of the performance due to the astigmatism induced by the tilted plates in the divergent beam inside the resonator. A schematic of the device is shown in Fig. 2.

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The device was composed of two identical uncoated CaF₂ plates tilted at opposite angles, thereby eliminating any offset due to transmission through a finite thickness plate. The plates were driven from 80° to 50° (surface normal with respect to optical axis) with a stepper motor drive pushing a conical piston 2 inches in translation, mechanically set between the nearest edges of the two mounted plates. The expected nonlinearity of the angular tilt with respect to the optimum translational drive was about +/- 8.8 arc-sec over the 30° range. This nonlinearity was tailored by adjusting the slope of a cone piston and position at which the linear surfaces of the plate mounts contacted the cone. The tilts of the mounted plates were accurately recorded and calibrated with respect to one another using a pair of theodolites in a triangulation metrology scheme. The as-built final values of nonlinearity were measured to be +/- 5.7 arc-min over the full 2 inch travel with a +/- 27 arc-sec variation every 0.1 inch. The final measured plate angles as a function of piston position were equal and opposite to within 36 arc-sec over the 2 inch travel. The wedge in the plates was matched to produce equal and opposite effects in the line-of-sight (LOS) transmission through the device. A final calibration provided a look-up table of tilt angles vs. piston translation for use in the remote control room of the FEL, thereby eliminating any effects due to the drive nonlinearity.

The size of the plates was chosen to allow ample clearance for the optical beam when at maximum tilt (minimum dimension 5ω , where ω is the half-diameter of the beam). The beam ω , for the position within the 7-m resonator at which the device was placed (reference Fig. 1), was about 5.9 mm, making the plate dimensions about 175x35mm. These dimensions allowed for 2.5-mm edge mounting for the most severe tilt of 80°. The thickness of the plates was chosen to be as thin as possible without compromising the fabrication tolerance of $\lambda/10$ ($\lambda = 0.63 \mu\text{m}$) transmitted wavefront substrates. The minimum thickness was desired due to optical path length (OPL) changes within the resonator cavity as the tilt of the plates was changed. The 5-mm thickness chosen, when doubled due to the pair of plates used, and doubled again considering the round trip required within the simple resonator configuration, resulted in OPL variations on the order of 3 mm over the 30° operating range of the Brewster device. One end of the resonator was remotely mobilized to accommodate this movement.

Since the device was designed to contain a 10^{-8} torr resonator vacuum, the enclosure for the apparatus was fabricated to allow for attachment to the existing conflat flanges of the resonator hardware. A 6-inch square piece of non-magnetic steel, approximately 14.5 inches long, was hollowed for the enclosure. Credit should be given to Ron Wrench, an FEL mechanical/technical contractor, for the fabrication of this system's hardware as well as much of the other hardware below. A picture of the uninstalled unit is shown in Fig. 3.

This unit functioned as per design and allowed remote control of the resonator losses during several successful days of FEL lasing. We have seen in the resonator optics that the CaF₂ substrates, after continual x-radiation, have turned a bluish tint. The Brewster plates, perhaps because of the limited time over which they were used, showed no sign of tinting.

2. OPTICAL-MODE RELAY LENS SYSTEM

This system was designed for relay and resizing of the resonator optical output mode during propagation to an amplifier undulator, the SAMOPA configuration of an FEL. The system is basically a three-lens relay allowing for variation of the resultant waist position over a range of +/- 1 m and minimum waist ω from 0.5-2 mm at a resonator-amplifier separation of about 14 m. The first lens was held fixed in its mount, while the other two lenses were remotely repositioned to allow for the above variations during operation. The intent was to identify the optimal positioning and size of the minimum waist ω within the amplifier undulator for maximum FEL amplifier extraction from this seed laser input.

An optical delay line was incorporated into the span of distance between the resonator and the relay system to allow for the temporal separation, 46 ns, between the optical pulse emanating from the resonator and the subsequent electron pulse from the resonator undulator. The electron beam was 'bent' out of the optical resonator path through a 150° bend, regrouped, and sent directly into the amplifier undulator. A trombone extension of the optical path was created such that the optical delay distance could be tuned to within 4 μm , well within the 15 ps temporal envelope comprising the electron pulse in the amplifier undulator. Optimum positioning of the optical pulse with respect to the electron envelope was to be investigated as well. Fig. 1 shows the optical layout of the relay path.

The relay lens substrates were CaF₂ with an anti-reflection (AR) coating. A negative and two positive lenses were incorporated for the design. The positive, plano-convex lenses were 3 inches in diameter while the central negative lens was only 2 inches in diameter. Several lenses were on hand allowing some freedom within the constraints defined by the FEL turn-magnet geometry. A lens combination allowing all the freedom required could not be found in our limited supply. The focal lengths of the final lenses were 564.7 mm for the first lens, -261.3 mm for the middle negative lens (optionally a replacement lens of -310.3 mm focal length was used as described below), and 1.0705 m for the third lens. The focal lengths quoted are for 3.0- μ m wavelength.

The final configuration required that the middle, negative lens be changed for cases where the desired minimum waist ω was in the range of 0.5-0.785 mm. The waist sizes ranging from 0.785-2.0 mm could be accommodated without changing of lenses. The maximum travel of the third lens was only 12.5 inch, which required 11 settings of the third stage for the full 1.5 mm of change in waist ω size. The change of the middle lens required 2 settings of the center 6 inch travel stage. In either of the two combinations above, the focal position could be varied anywhere within the 2-m amplifier undulator with only about 150- μ m change in minimum ω . Pinning assemblies locating the last two lens' stages allowed for accurate positioning, although not remotely, without realignment. An adequate repeatable mount for the center lens was never engineered for the eventuality of a lens swap. The waist ω was initially required to be above 0.785 μ m, identifying the required negative lens. If a smaller waist ω had been required for the experiment at a later date, the decision was made that alignment metrology would have been brought into the FEL vault for accurate placement of the lens.

The metrology used for placement of these lenses incorporated an alignment telescope viewing virtual images of a laser point source reflected from the individual surfaces of the lenses. The manipulation of the lenses eliminated effects due to wedge in the optics and resulted in tilt/placement of the lenses on the optical axis to within 5 arc-sec/0.001 inch respectively. The AR coatings for 3.0 μ m allowed enough reflection at 0.63 μ m to view the laser images by eye through the telescope. This alignment was seen to hold to these tolerances over the complete travel ranges of the translation stages used. A repeatably mountable reference etalon was placed downstream of the lens system to allow for alignment of the system onto the optical axis of the amplifier undulator. The system was carefully transported from an evaluation lab to the FEL site after alignment.

The sensitivities of the placement of the lenses with respect to the waist position and size were analyzed in CodeV. The position of the waist within the amplifier, assuming the center/final lens could be accurately placed to within 10 μ m, could be known to within 1.15/0.07 mm, respectively. These same 10- μ m changes for the center lens induced less than 0.046% change in the minimum waist ω sizes and more than an order of magnitude less for the final lens' movements. In all cases, the most sensitivity to position was at the larger waist sizes positioned farthest from the relay system.

A second tier was assembled above the platform on which the lens stages were attached. This provided an area where a beamsplitter pickoff could send a portion of the beam to be used for alignment and diagnostics. These optical diagnostics were never assembled, unfortunately, because the amplifier undulator was never installed. Fig. 4 shows the relay lens assembly in place in the FEL vault.

3. SPECTRAL HARMONICS BAND-FILTERING SYSTEM

This system was comprised of uniquely chosen stock filters allowing for the selection and individual intensity measurements of the 2nd through 8th harmonics of the FEL fundamental output, nominally expected at 3.0 μ m with variations ranging from 2.45-3.25 μ m (reference Table 1 below for the wavelength ranges of interest). The vendors from which these filters were purchased will be identified in order that the set could be reproduced if required. The transmission ranges will be quoted using the 50% transmission points (FWHM) for all filters below. In all cases, purchased filters were chosen that gave the highest transmission.

Table 1: FEL Harmonic Ranges

<u>Wavelength</u>	<u>Harmonic</u>	:	<u>Wavelength</u>	<u>Harmonic</u>
2.450-3.250	Fundamental	:	0.490-0.650	5th
1.225-1.625	2nd	:	0.408-0.542	6th
0.817-1.083	3rd	:	0.350-0.464	7th
0.613-0.813	4th	:	0.306-0.406	8th

The detectors to be used for analysis of the transmitted signal never matured much further than the realization that it would be a UV-sensitive photomultiplier (PMT) (Hamamatsu 552S), due partially to its spectral response as well as the sensitivity required to identify the 7th-8th harmonics, which had approximately 6-7 orders of magnitude less energy than the 2nd harmonic (each harmonic was essentially an order of magnitude weaker than the harmonic above it). By using a mercury cadmium telluride detector for wavelengths above 2 μm , a silicon detector whose sensitivity dropped at 1.2 μm , or a PMT whose sensitivity dropped in the upper visible, a balance between the higher energy 2nd harmonic and the lower energy 8th harmonic could be established. The transmission curves of the band filters discussed and the effect of the detectors are reproduced in Fig. 5.

The FEL output was to be initially filtered using a National Photocolor inconel-coated beamsplitting pellicle, which would split a spectrally uniform percentage of the incident light to the diagnostic station at which the harmonic filters were located. The low cost of this optic allowed for several to be purchased for the price of a single multi-layer broadband dielectric beamsplitter. The pellicle reflectivity/transmissivity was only about 30%.

The spectrum from the UV through the visible is broken up into overlapping segments as described below in Table 2. In most cases, the bandpass is created using a pair of filters composed of a longpass and shortpass combination. Leading/trailing edge slopes for the long/short pass filters are defined as follows

$$\text{Slope} = 100 (\lambda_{95} - \lambda_5) / \lambda_5 \quad (3)$$

where λ_x is the wavelength at which the transmittance is x% of the peak. The transmission bands from the filter sets overlap with the sets on either side, but since the fundamental will be at only one position within the expected range during any one set of measurements, this poses no problem. Since the bands are so close together in the UV region of the spectrum, some creative subtracting of higher bands from the readings would probably be required.

Table 2: Harmonic Bandpass Filter Sets

Vendor	Wavelength Band (μm)	Trans. Avg. %	Sub- harmonic	Lead/Trail Edge Slope %
Andover (775-FW82)	1.20-3.00+	85	Assrt	
Optical Filter Corp. (W01520)	1.22-1.82	90	2	10.4/
Optical Filter Corp. (W00945)	0.82-1.06	76	3	12.2/4.7
Spectrogon (SSP-1125)	0.88-1.13	60	3 (alternate)	
Schott (RG9) + Corion (LS-800)	0.73-0.80	50	4	6.3/8.0
Schott (RG665) + Corion (LS-750)	0.66-0.75	50	4	5.2/8.1
Schott (RG630) + Andover (700-FLO7)	0.63-0.70	76	4,5	6.4/6.9
Schott (OG550) Andover (600-FLO7)	0.59-0.65	84	4,5	6.2/3.1
Schott (OG590) + Andover (650-FLO7)	0.55-0.60	79	5	4.0/2.9
Schott (GG495) + Andover (550-FLO7)	0.49-0.55	77	5,6	6.4/5.9
Schott (GG420) + Andover (500-FLO7)	0.42-0.5	79	6	10.3/2.7
Andover (450-FLO7)	0.37-0.45	90	6,7,8	15.1/6.0
Schott (UG11)	0.30-0.35	81	7,8	19.8/9.0

The filter used for the passing of the 2nd harmonic is rather broad, and a mercury cadmium teluride device could be used for this signal. A retransmission band begins at about $2.8\text{ }\mu\text{m}$, but would be of little concern if a Germanium window were inserted to filter the harmonics from the fundamental, and then a subtraction performed between the 2nd and 3rd harmonic readings. The 3rd-4th harmonic filters also have a retransmission beginning above $1.2\text{ }\mu\text{m}$, but a silicon detector would not be sensitive to those wavelengths. The 5th and higher harmonic filters also contain retransmission bands which would allow transmission of the more intense lower harmonic signals. The Hamamatsu 552S PMT would be insensitive to wavelengths above $0.9\text{ }\mu\text{m}$, eliminating these problem areas. A "hot mirror" Andover filter (#775-FW82) can also be placed in combination with any of the bandpass filters in the visible, to suppress any retransmittance at NIR wavelengths until about $1.2\text{ }\mu\text{m}$.

The mounting for these filters and combinations of filters would have varied between translation stages and filter wheels. All filters were 2" square for mounting into existing hardware. A broad-band polarization filter would also have been utilized in the beam for adjusting the intensity of the individual harmonics. Radiation shielding of these optics, as well as the remainder of the FEL optical diagnostics, was accomplished using lead bricks to minimize the effect of the x-radiation.

4. 25-nm RESOLUTION MICROPULSE SPECTROMETER

The spectral variability of individual micropulses, nominally 15-ps width separated by 46 ns, was to be investigated using a Spiricon 1x32 pyroelectric array. The spectral range over which the device was to be used varied from $2.45\text{--}3.25\text{ }\mu\text{m}$. When spread over the 32 elements of the array, this results in a 25-nm spectral resolution. The design incorporated two lenses, a grating, and the array detector. The associated hardware allowed the system to be aligned and placed onto the LANL FEL optical diagnostic table. Unfortunately, the time/expertise required for the calibrated hookup of the Spiricon detector with the temporal resolution required for the individual micropulse measurements was unaffordable during the last years of the operation of the LANL FEL. Therefore, this section describes the system but cannot report on the use of the device. The initial intention was to allow measurement of the fluctuation, within the set of individual micro-pulses forming a macro-pulse, of the spectral output of the FEL.

The IR output of the FEL was transported several meters onto the optical diagnostic table, as shown in Fig. 1. The output was essentially collimated, with a nominal waist ω of about 2.3 mm. This beam was brought to an intermediate focus using a CaF₂, 1-inch diameter, 50mm focal length lens. Another CaF₂, 2-inch diameter, 100-mm focal length lens collimated this focused beam, but was displaced 5 mm off axis in what we will call the Y direction, normal to the table. The focal lengths are quoted for $5.0\text{ }\mu\text{m}$ wavelength. The collimated output from this second lens, is directed toward a 1x2" planar-rectangular grating, 150 lines/mm, blazed for 1st order at $6\text{ }\mu\text{m}$ at an angle of 26.7° . The spacing between the tilted grating, tilted about the Y axis at the blaze angle, and the 2-inch diameter lens was minimized at 13 mm to allow for minimum aberration of the diffracted beam at the extreme wavelengths. The diffracted illumination is again collected by the 2-inch diameter lens and focused onto the opposite side of the offset optical axis of the 2-inch diameter lens, at about 10 mm in the Y direction from the original input optical axis. The plan and elevation views of the optical schematic are shown in Fig. 6.

The linear spread in the diffracted illumination between the $2.45\text{--}3.25\text{-}\mu\text{m}$ extremes covered the 1-inch detector width. The off-axis aberrations in the focused beams of the different wavelengths were analyzed in CodeV and found to fit within the boundaries defined by the $0.4\times 0.8\text{-mm}$ rectangular pixels of the detector. The detector was housed behind a tilted ZnSe window, which formed a vacuum enclosure for the pixels.

The alignment of the system followed the same procedure outlined in the optical mode relay lens system, where a virtual laser source is viewed from each surface of the lenses. Offsets were calibrated using steel measurement standards. The lenses were mounted in 5-axis mounts allowing for ease of adjustment. The grating was referenced in the zero-order to the optical axis and then rotated to its proper position, calibrated beforehand using a triangulation scheme with two theodolites and referenced using a dowel-pin plate. A $25\text{-}\mu\text{m}$ pinhole was accurately placed at the incoming focal position in such a way as not to interfere with the detector focal plane. This allowed alignment of the input beam into the device by simultaneously forcing the beam through the center of the input lens and the pinhole. Fig. 7 shows the assembly in position on the LANL optical diagnostic table.

5. 12.5nm RESOLUTION MICROPULSE SPECTROMETER

Using the same input lens and overall description as described in the 25-nm case above, if the focal length of the second lens is doubled, the linear separation at the eventual focus due to diffraction of the extreme wavelengths also doubles, now covering 2

inches. If a coated fold flat with a sharp front edge, created by placing a 45° chamfer on the back surface, is placed such that one half of the spectral spread is turned by 90°, another detector could be placed to receive that information, thereby doubling the resolution of the device. The spot sizes over the entire range still fit within one pixel of the detector as well, although they are slightly larger than the 25-nm resolution case. The specially made Spiricon detectors are rather bulky, being mounted on a 6x10" electronics card, but by inverting one with respect to another, there appeared to be plenty of space available.

6. 0.59-nm RESOLUTION MICROPULSE SPECTROMETER

Using the same general configuration as described in the 25-nm case above, the 0.59-nm resolution can be obtained by changing all three optical elements. The input lens' focal length is lengthened by a factor of 2.5, the second lens' focal length is increased by a factor of 10, and the grating changed to one that is blazed at 64.2° for 3.0 μm , with 600 lines/mm (the original grating could have been used). Two fold mirrors were required between the two lenses to allow the system to be fit within the constraints defined by the densely packed optical diagnostics table. The extreme wavelengths are identified such that the linear separation will just fill the 1-inch length of a single Spiricon detector. The resultant spectral band now measurable on the detector is from 2.990-3.009 μm . A monochromatic spot size easily fits into one detector pixel, 0.4x0.8 mm in size.

The expected spectral bandwidth of the FEL is on the order of 0.08%. This would imply that the instantaneous signal on the detector would cover as many as 7 pixels simultaneously, assuming FWHM values of about 1.2 nm. The sensitivity of the detector was judged to be adequate to allow the centroid of the spectral spread to be identified by noting the maximum energy on the group of 7 pixels. Refinements in the readout were expected to bring down the resolution even further.

7. REFLECTIVE MODE PROFILE ROTATOR

This device was designed to allow for the rotation of the spatial mode of any optical beam, without chromatic effects. The device was required to allow the investigation along different axes through the spatial mode profile using the Spiricon detector described under the 25-nm spectrometer section. Using a single detector, the beam could be rotated spatially, with a 2x magnification in angle, by sending the beam through this rotator on its way to the detector. The operation is exactly the same as that of a Dove prism³, but since the device was slated to be used at 3.0 μm at LANL, 10.06 μm at Boeing, and possibly in the visible to UV wavelengths again at LANL, it was made from reflective components.

Two 1.25x3.25-inch rectangular mirrors, tilted at 80° to the incoming beam in opposite directions, and a 2-inch diameter mirror comprise the optical components of the device. The first rectangular mirror tilts the beam such that it is inclined at 40° to the incident beam optical axis. The round mirror, set such that its surface is parallel to the original optical axis, reflects the tilted beam onto a second rectangular mirror, which sends the inverted image onto its original axis of propagation. The mounted mirrors were on the order of $\lambda/20$, $\lambda = 0.6328 \mu\text{m}$. The final propagation pointing error, 98- μrad maximum, was gauged using double-pass interferometric techniques during rotation. Fig. 8 shows a schematic view of the device from the side, while Fig. 9 shows the unit as-built.

8. SUMMARY

The engineering and design for the use of these optical diagnostic subsystems may never be fully utilized, but the analysis seems to provide some reassurance that the unused devices would indeed have performed as designed. The Brewster device demonstrated to the FEL community that an intracavity device could indeed be used for control of the gain within the resonator, barring considerations of optical distortion and damage for higher power FELs.

The band filtering, relay lens system, and reflective Dove prism assemblies were included in this paper to summarize optical efforts for the initial direction of the LANL FEL objectives. The fast spectrometer detectors would have been a leading edge technology for measurement of intensity related functions on extremely short laser pulses.

Many of the LANL optical diagnostic instruments may again surface in the Seattle based Boeing FEL, Advanced Power Laser Experiment (APLE)⁴, currently progressing at reduced funding.

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10. FIGURES

Figure 1: The optical layout for the FEL resonator, optical diagnostic path, and amplifier relay.

Figure 2: Schematic of the Brewster plate attenuation device. The CaF₂ plates are mounted in Aluminum frames moved by a conical - topped piston.

Figure 3: The as-manufactured Brewster plate assembly.

Figure 4: Views from both ends of the amplifier relay lens assembly. The CaF₂ lenses are mounted in aluminum cells on remotely operated translation stages.

Figure 5: The FEL harmonic bandpass filters created from high/low pass combinations with normalized detector sensitivities considered.

Figure 6: Optical layout of the micropulse spectrometer in the plan and elevation views. The simulated grating effect is shown as a tilt in the plan view. The ZnSe window and CaF₂ lenses are shown.

Figure 7: The as-manufactured micropulse spectrometers showing the lens cells, grating, and the unwired linear array detector.

Figure 8: The schematic of the a reflective version of the Dove prism. The chromatic effects of a prism are eliminated allowing spatial mode rotation across the spectrum.

Figure 9: The as-manufactured spatial mode rotator. Rotation is magnified 2x.

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