DESIGN OF A SINGLE-SHOT PRISM SPECTROMETER IN THE NEAR- AND MID-INFRARED WAVELENGTH RANGE FOR ULTRA-SHORT BUNCH LENGTH DIAGNOSTICS*

C. Behrens[†][‡], A. Fisher, J. Frisch, S. Gilevich, H. Loos[§], J. Loos
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

The successful operation of high-gain free-electron lasers (FEL) relies on the understanding, manipulation, and control of the parameters of the driving electron bunch. Present and future FEL facilities have the tendency to push the parameters for even shorter bunches with lengths below 10 fs and charges well below 100 pC. This is also the order of magnitude at laser-driven plasma-based electron accelerators. Devices to diagnose such ultra-short bunches even need longitudinal resolutions smaller than the bunch lengths, i.e. in the range of a few femtoseconds. This resolution is currently out of reach with time-domain diagnostics like RF-based deflectors, and approaches in the frequency-domain have to be considered to overcome this limitation. Our approach is to extract the information on the longitudinal bunch profile by means of infrared spectroscopy using a prism as a dispersive element. In this paper, we present the design considerations on a broadband single-shot spectrometer in the near- and mid-infrared wavelength range ($0.8 - 39.0\,\mu$m).

INTRODUCTION AND MOTIVATION

The Linac Coherent Light Source (LCLS) at SLAC is routinely running with 20 pC bunch charge and produces X-ray pulses with lengths below 10 fs [1]. Other existing facilities like FLASH at DESY or the planned European XFEL have the same tendency to push the accelerator parameters for low charge operation resulting in ultra-short electron bunches and photon pulses [2]. The upper plot of Fig. 1 shows simulations of the longitudinal bunch profile for ultra-short bunch operation at LCLS. In order to diagnose such short bunches sufficiently, devices with time resolutions well below 10 fs are desired. This is currently out of reach with standard time-domain diagnostics like RF-based deflectors in the S-band, but becomes possible with future X-band technology. In order to demonstrate the ultra-short bunch lengths, a dedicated time-domain experiment was carried out successfully [3], but this is by no means a robust diagnostics for regular operation. The opposite approach is in the frequency-domain and relies on the fact that the longitudinal bunch profile is encoded in the spectrum of radiation generated by electron bunches like from transition radiation. The interesting wavelength range

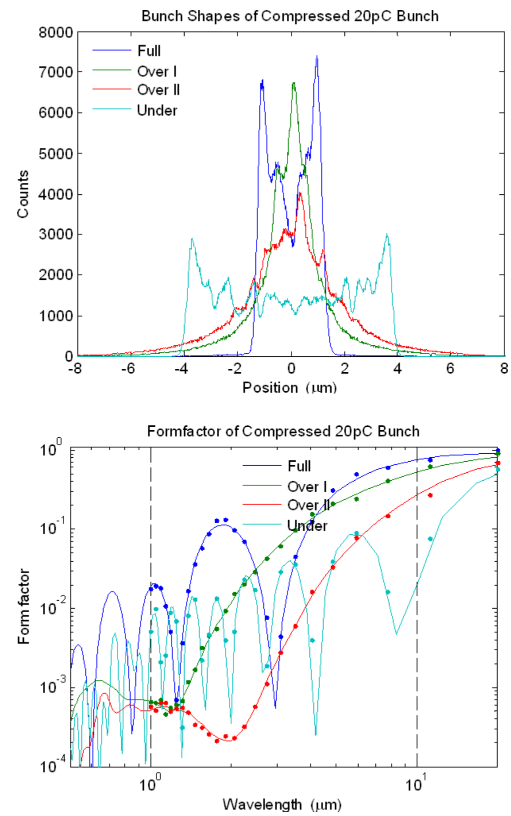

Figure 1: Simulations for ultra-short bunch operation with 20 pC bunch charge at LCLS. Top: Longitudinal bunch profile for different compression scenarios. Bottom: Corresponding longitudinal form factors, i.e. the information on the longitudinal profile in the frequency-domain.

for bunch length diagnostics is in the infrared with standard methods of spectroscopy available like in [4], where multi-staged reflective blazed gratings were used to reconstruct the longitudinal bunch profile. If the wavelength range necessary to reconstruct the bunch shape is in the near- and mid-infrared, like from $1 - 20\,\mu$m for the ultra-short $1 - 2\,\mu$m rms bunches shown in Fig. 1, a prism spectrometer might be the better option, because there is no need for complicated and expensive multi-stage setups.

DESIGN CONSIDERATIONS

The prism material used for spectroscopy needs two specific properties; good transmission and a sufficient material dispersion (wavelength dependence of the index of re-

* Work supported by US DOE contract DE-AC02-76SF00515.
† On leave from DESY, Hamburg, Germany
‡ christopher.behrens@desy.de
§ loos@slac.stanford.edu

fraction $D_M = \frac{dn}{d\lambda}$) in the designated wavelength range. For broadband spectroscopy in the near- and mid-infrared, Zinc Selenide (ZnSe) and Thallium Bromo-Iodide (TlBr-TlI, KRS-5) is the material of choice. According to Fig. 2, both materials offer transmission from optical wavelengths up to about 20 μm for ZnSe and 40 μm for KRS-5, strong dispersion at short wavelengths and moderate dispersion in the mid-infrared. Prism spectrometers are operated in the

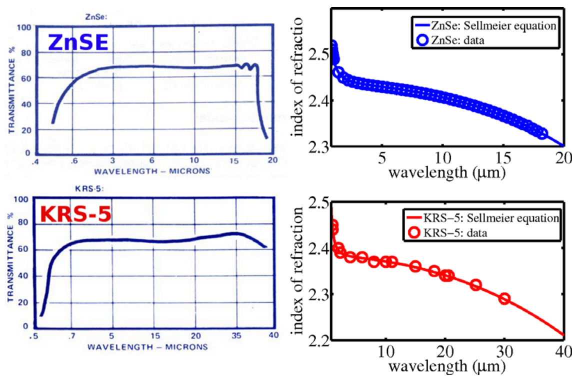

Figure 2: Transmission characteristics [5] and index of refraction according to data from literature [6, 7] and Sellmeier equation: ZnSe (top) and KRS-5 (bottom).

region of minimum deflection δ_{min}, where the angle difference δ between incoming and outgoing rays has a minimum. In this case, the rays within the prism are symmetric and the deflection is independent of the incoming angle. The minimum deflection angle $\delta_{min}(n(\lambda), A)$ is a function of the index of refraction $n(\lambda)$, i.e. the material, and the apex angle A of the prism. The resolution power $R = \frac{\lambda}{\Delta\lambda}$ of a prism spectrometer is given by $R = D_A \cdot w_p = \frac{d\delta_{min}}{dn} \cdot D_M \cdot w_p$ with the angular dispersion $D_A = \frac{d\delta_{min}}{dn}$ and the waist of the incoming rays at the prism w_p. The left plot of Fig. 3 shows the wavelength resolution normalized to wavelength λ and waist w_p (which is D_A^{-1}). Assuming $w_p = 10$ mm and KRS-5 with $A = 10°$, the wavelength resolution $\Delta\lambda$ is about 2.1 μm at the peak around $\lambda \approx 6.5\,\mu$m. Using a larger apex angle, or ZnSe as prism material would result in a better resolution, but also in a smaller wavelength coverage $[\lambda_{min}, \lambda_{max}]$ of the spectrometer, which is shown in the right plot Fig.3. The reason is that the dispersed radiation after the prism has to be focused with a certain focal length onto a detector with a limited sensor size.

For this spectrometer design, the sensor size has a length of 12.8 mm and the last mirror in front of the detector has a focal length of $f_2 = 177.8$ mm. Off-axis parabolic mirrors will be used in order to be insensitive to chromatic aberration. The spectrometer will be equipped with a KRS-5 prism with an apex angle of 10° which allows spectroscopy from the optical wavelength range up to 40 μm (see right plot of Fig.3). For higher resolution and a corresponding smaller wavelength coverage, ZnSe can be used as an option.

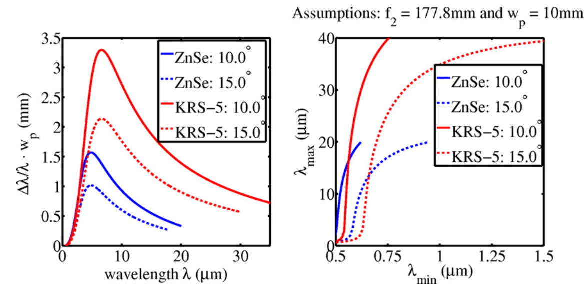

Figure 3: Spectrometer characteristics for different apex angles A of the ZnSe and KRS-5 prisms. Left: Wavelength resolution normalized to wavelength and radiation waist w_p at the prism . Right: Obtainable wavelength coverage from λ_{min} to λ_{max} with assumptions on f_2 and w_p.

OPTICS CALCULATIONS

The dispersion of light through prisms is the necessary effect for spectroscopy, but also introduces chromatic effects due to the wavelength dependent deflection angles. In order to investigate possible imaging errors, a ray-tracing simulation, using ZEMAX[8], for wavelengths 0.8-39 μm was performed (see Fig.4). The simulation includes two off-axis parabolic mirrors with 90° deflection angle, a KRS-5 prism with $A = 10°$, and a detector plane with a length of 12.6 mm. The lower plots of Fig.4 show the wavelength dependent focal plane which is not perpendicular to the optical axis (defined by the center wavelength of 19.9 μm). A detector tilt of about 44° (found empirically)

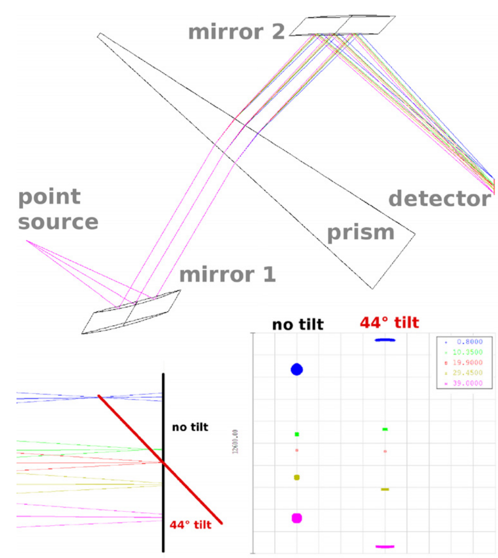

Figure 4: ZEMAX[8] simulation of the spectrometer configuration with KRS-5. The lower plots show the focal plane on the detector for different wavelengths (unit: μm) and a detector tilted by 44° w.r.t the optical axis.

has to be introduced for correction. After correction, the effective detector range is reduced, but it is still possible to cover the wavelength range 0.8-39 μm.

LINE ARRAY DETECTOR

For the detector component of the device, a linear 128 element (pixel) line sensor array was chosen from Pyreos [9] which is composed of a thin-film pyroelectric material with high sensitivity (see Fig. 5). The 128 channels are readable with frequencies from 10-128 Hz. Exact measurements of the sensitivity were not available in the product information, so a test was conducted to determine the sensitivity of the array. A low-powered HeNe laser (0.9 mW) was placed in front of a chopper wheel (120 Hz), and a lens was used to focus the chopped beam onto the array. The peak-to-peak voltage reading from the array on the scope was 328 mV (over about 20 pixels where the laser illuminated the array). Therefore, the total energy was around 7.5 μJ, or 0.375 μJ per pixel, giving a sensitivity of $0.328\,\mathrm{V}/0.375\,\mu\mathrm{J/pixel} = 0.875\,\mathrm{V}/\mu\mathrm{J/pixel}$.

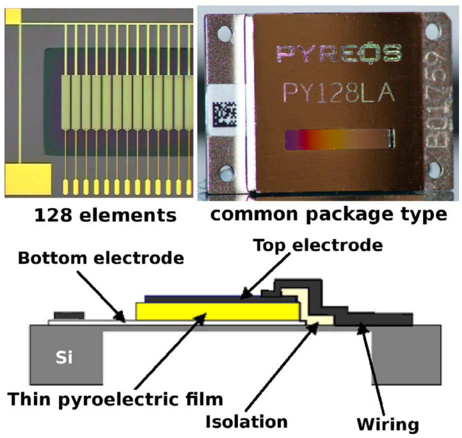

Figure 5: Line-array detector made of 128 thin pyroelectric film sensors [9]. Top: View on the single elements, and the entire detector unit with cut-out for the sensor array. Bottom: Sketch of the sensor assembly (cross section).

As the test board (included with the sensor array) was not necessary for the final design, a peripheral interface controller (PIC) was programmed using assembly code to establish the appropriate clock frequencies which regulate the read-out cycle and individual readings from each pixel, and will be used with the sensor array on a smaller, simpler printed circuit board (PCB). With the internal oscillator set to 16 MHz, five clock frequencies were programmed on the PIC chip, each with a different setting: 7.5 μs, 30 μs, 400 μs, 15 μs and 66 kHz (read-out clock). The PCB to be used includes the PIC chip which receives the input trigger (from the electron beam timing system), the sensor array connected to clock signals from the PIC chip, a reference voltage chip connected to the sensor array chip, and an op-amp between the sensor array chip and the analog output.

PROTOTYPE LAYOUT FOR LCLS

A potential prototype layout of the spectrometer for LCLS is shown in Fig. 6. A standard diagnostics station will be equipped with a viewport made of KRS-5 to have good transmission in the mid-infrared. In order to prevent absorption in humid air, the whole spectrometer, including transport optics, will be located in a box suited for flushing with N_2 or dry air. The spectrometer and transport optics will consist of 90° off-axis parabolic mirrors 2″ in diameter, and the entire setup turns out to be very compact.

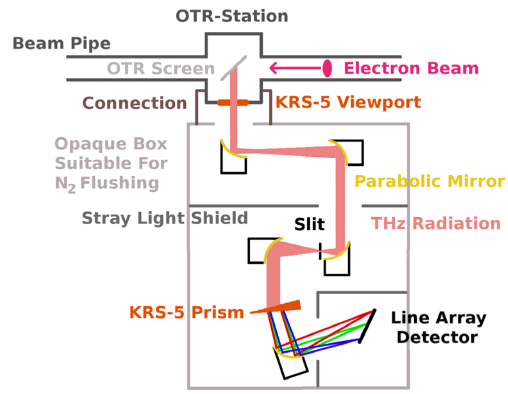

Figure 6: Prototype spectrometer layout for LCLS, including radiation transport optics and KRS-5 viewport.

CONCLUSIONS

We have presented a design of a prism spectrometer for the operation in the near- and mid-infrared wavelength range dedicated for ultra-short bunch length diagnostics. We showed the possibility to cover the broad wavelength range from 0.8-39 μm using a KRS-5 prism. Simulations were used to investigate and correct imaging errors on the detector plane. A prototype layout for LCLS is available and the alignment and assembly work is in progress.

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