

A LOW TIME-DISPERSION REFRACTIVE OPTICAL TRANSMISSION LINE FOR STREAK CAMERA MEASUREMENTS

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Abstract

Streak camera measurements of the electron bunch length are limited in resolution by several factors. These include: (1) the light source itself (e.g. OTR, Cherenkov, Synchrotron radiation), (2) dispersion from the refractive optical transport line (OTL) between the light source and the streak camera, and (3) the streak camera itself. The limiting resolution for pulses length of a few psec is caused by the OTL due to the very broad bandwidth of the light pulse (hundreds of nm). While an all-reflective OTL can eliminate dispersion, the system is complicated and expensive.

In this paper, we examine the time spread of the light pulse due to the dispersion in the lenses of the OTL. We present an analysis of the dispersion and benchmark it to measurements of the time dispersion for several different lens materials. Finally, we conclude with recommendations of the proper design of the refractive OTL to minimize the time dispersion while maximizing the signal.

STREAK CAMERA MEASUREMENTS OF THE ELECTRON BUNCH LENGTH

Streak camera measurements of the electron (in general, charged particle) bunch length are well suited for the regime of greater than a few picoseconds. Our examples are based on a Hamamatsu [1] C1587 streak camera with a resolution of 2ps since this is the camera we own at the Argonne Wakefield Accelerator (AWA) Facility. Note that there exist streak cameras with significantly better resolution such as the Hamamatsu Fresca-200 with a resolution of 200 femtoseconds. In any case, the examples here can be extended to any particular case as long as one requires that the dispersion introduced by the optical transport line is less than one third of the minimum bunch length one desires to measure since this only introduces an error of less than ~5% ($\sqrt{1^2 + 0.33^2} = 1.05$).

A typical setup for the measurement of the electron bunch length is shown in Fig. 1. (1) The process begins when the electron bunch passes through the radiator (e.g. OTR) and generates a prompt, broadband, light pulse, of similar transverse and longitudinal profile to the electron bunch. (2) To avoid damage to the streak camera it is typically located far from the radiator and therefore the light pulse is often transported through a long, refractive, optical transport line (OTL) made up of a series of *glass* lenses [2]. Other solutions are possible, such as an all reflective OTL or to locate the streak camera near the radiator with adequate shielding, but we only consider the case of a long, refractive OTL in this paper. (For the remainder of the paper, we use the shorter phrase "OTL" to refer to "a long, refractive OTL".) The problem with the OTL is that light pulse length increases as it travels through the OTL due to the variation of the group velocity with frequency (a.k.a. group velocity dispersion) in the glass (pulse at bottom of Fig. 1). This means that by the time the light pulse arrives at the streak camera its length is significantly longer than the electron's bunch length. A bandwidth filter of ~10nm is typically used to reduce the lengthening to an acceptable level. (3) Finally, the light pulse arrives at the streak camera for measurement. Proper use of the streak camera is beyond the scope of the paper so we limit comments to bandwidth requirements of the streak camera since it has direct bearing on the subject of this paper. The bandwidth of the streak camera is determined by the input optics and the photocathode quantum efficiency. The AWA streak camera uses the N1643 streak tube with bandwidth of [200-850nm] and we used this for the examples in this paper.

REFRACTIVE AND GROUP INDEX

Dispersive media are characterized by a wavelength (or frequency) dependent susceptibility $\chi(\lambda)$, refractive index $n(\lambda)$, and group index $n_g(\lambda)$ [3]. The refractive index of

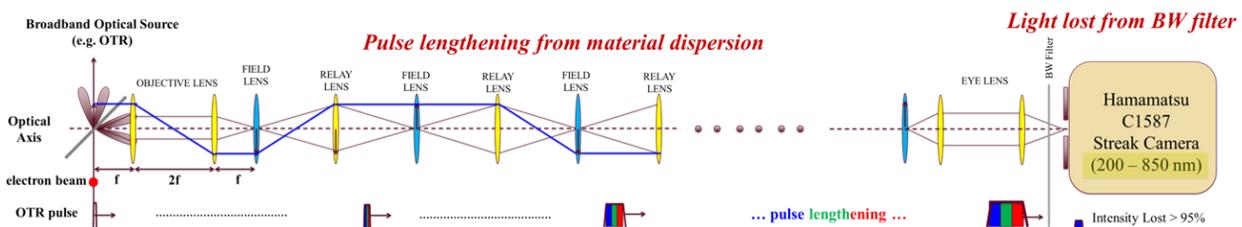


Figure 1: Setup for a Streak Camera based bunch length measurement.

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optically transparent media is well described by the Sellmeier equation far from the resonances λ_i ,

$$n^2(\lambda) = \chi_{00} + \sum_i \chi_{0i} \frac{\lambda^2}{\lambda^2 - \lambda_i^2} \quad (1)$$

where χ_{0i} is the real susceptibility at the resonances λ_i .

The group index $n_g(\lambda)$, is related to the refractive index through the equation,

$$n_g(\lambda) = n(\lambda) - \lambda \frac{dn(\lambda)}{d\lambda} \quad (2)$$

Plugging (1) into (2) gives,

$$n_g(\lambda) = n(\lambda) - \frac{1}{n(\lambda)} \sum_i \chi_{0i} \frac{\lambda^2 \lambda_i^2}{(\lambda^2 - \lambda_i^2)^2} \quad (3)$$

In this paper, we considered 6 different kinds of glass materials. Sellmeier coefficients are available for a wide variety of optical materials [4] including crystals and glasses. Table 1 lists the coefficients for the six glasses used in this paper and Fig. 2 shows $n(\lambda)$ in blue and $n_g(\lambda)$ in red.

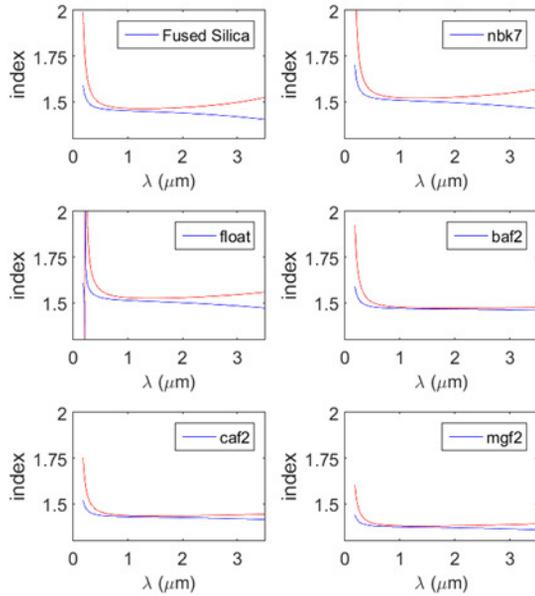


Figure 2: Refractive index $n(\lambda)$ in blue and Group index $n_g(\lambda)$ in red.

The optical pulse travels through the glass at the group velocity given by, $v_g(\lambda) = c/n_g(\lambda)$. Comparison of $n_g(\lambda)$ for all six materials shows (Fig. 3) that MgF_2 has

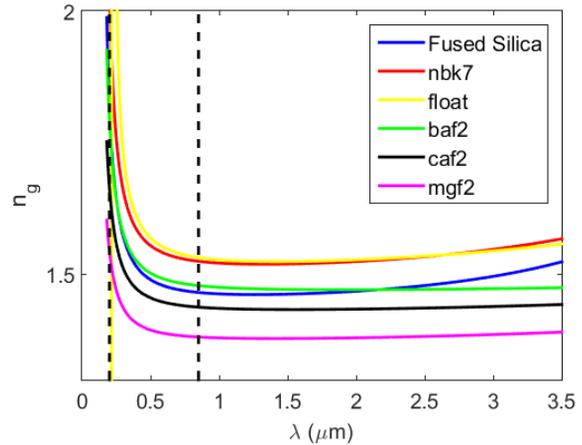


Figure 3: Group index for six different glasses. Dotted lines bracket the streak camera spectrum: [200-850nm].

the lowest group index while float and N-BK7 have the highest.

The group delay through the glass is $\tau(\lambda) = L/v_g(\lambda)$, where L (100mm in this paper) is the length of glass. Using this, we find the absolute delay of a light pulse moving through the glass compared to a light pulse moving through vacuum as: $\delta t(\lambda) = L/c * (n_g(\lambda) - 1)$ and plot the result on the left hand side of Fig. 4.

However, it is not the value of $\delta t(\lambda)$ that determines the spreading of the optical pulse in the glass but rather the spread of group velocity (over the bandwidth). This is often treated with a Taylor expansion around λ_0 (a.k.a. group velocity dispersion) when the bandwidth is small but we cannot do that here given the very large bandwidth. Therefore, the parameter we are interested in is the relative delay which is the difference between the delay and the minimum absolute delay in the bandwidth, $\delta t(\lambda) - \delta t_{min}$. The relative delay is plotted in Fig. 4 on the right and the wavelength which corresponds to δt_{min} is shown; values are in the near IR. This value of the wavelength near the minimum would be the ideal operating point to minimize lengthening, but the streak camera bandwidth does not extend into the near IR.

Table 1: Sellmeier Coefficients for the Six Materials Analysed

| Material | χ_{00} | χ_{01} | λ_1 | χ_{02} | λ_2 | χ_{03} | λ_3 |
|------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Fused Silica | 1 | 0.683740 | 0.0678493 | 0.420323 | 0.1157449 | 0.585027 | 8.030770 |
| N-BK7 | 1 | 1.039612 | 0.0774641 | 0.2317923 | 0.1414846 | 1.010469 | 10.176475 |
| float | 1 | 1.237958 | 0.0929021 | 0.04666468 | 0.2165812 | 2.467005 | 16.252578 |
| BaF ₂ | 1.33973 | 0.81070 | 0.10065 | 0.19652 | 29.87 | 4.52469 | 53.82 |
| CaF ₂ | 1.33973 | 0.69913 | 0.09374 | 0.11994 | 21.18 | 4.35181 | 38.46 |
| MgF ₂ | 1.27620 | 0.60967 | 0.08636 | 0.0080 | 18.0 | 2.14973 | 15.0 |

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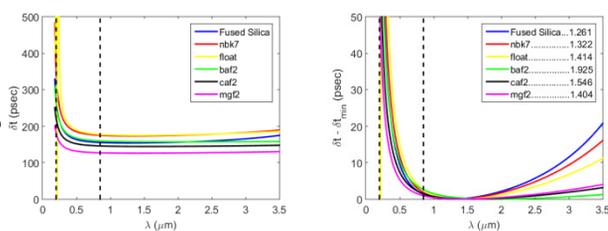


Figure 4: The absolute (left) and relative (right) delay of the light pulse traveling through glass of $L=100\text{mm}$. The numbers are the wavelength of minimum relative delay.

Now that we know the relative time delay of the OTL we wish to determine the region of the spectrum that will give us the maximum bandwidth for a certain resolution requirement. For example, if we require the OTL lengthening to be less than 1 psec, then we calculate the width of the spectrum that fits in a window (box in Fig 5) of height = 1 psec (Fig. 5, left). From this we calculate the bandwidth as a function of l (Fig. 5, right). This shows that using MgF2 can use a bandwidth filter of 147nm if one starts at 703nm. In contrast, N-BK7 needs a 6nm bandwidth filter if starting at 400nm.

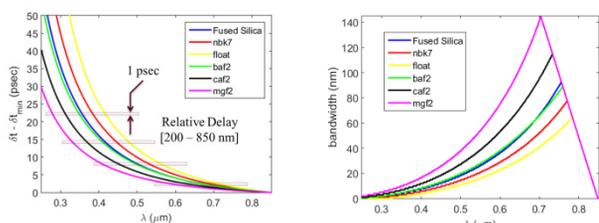


Figure 5: Determination of the bandwidth corresponding to the OTL time spread of 1 psec within the streak camera spectrum.

To maximize the streak camera signal we wish to maximize the number of photons, N_{ph} , striking the photocathode. (This ignores the QE of the photocathode.) The OTR spectrum, N_{ph} as a function of wavelength [5] can be found from,

$$\frac{dN_{ph}}{d\lambda} = \frac{2\alpha}{\pi\lambda} \left\{ \ln\left(\frac{\gamma\lambda}{\lambda_{pe}}\right) - 1 \right\} \quad (4)$$

Where α is the fine structure constant, λ_{pe} is the plasma wavelength (83.5nm for aluminium) and γ is the Lorentz factor. By convolving the OTR spectrum (Eq. 4, $\gamma=40$ & $Q=1\text{nC}$) with the bandwidth (Fig. 5, right) we can calculate the signal strength to the streak camera (Fig. 6).

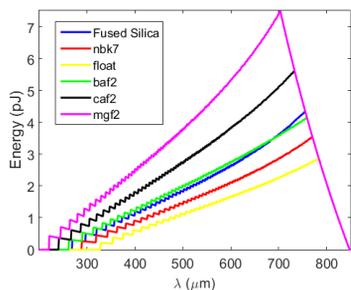


Figure 6: Signal strength at streak camera entrance.

COMPAISON TO EXPERIMENT

An experiment was carried out to benchmark the analysis presented in this paper (Fig. 7) by measuring the absolute delay. A short laser pulse (we used 248nm, 372nm, and 744nm) was split (S) so that one pulse travelled through glass and one did not and the difference of the arrival of the pulse was measured with the streak camera.

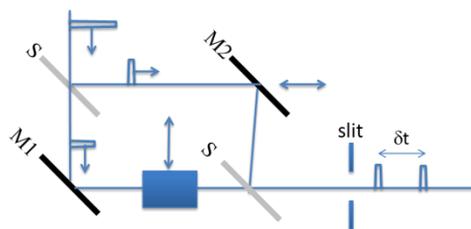


Figure 7: Setup used to measure the absolute delay.

The agreement between the analysis and the experiment is decent but not great (Fig. 8). The best agreement occurs with the fused silica data likely because the Sellmeier coefficients were provided by the vendor whereas the other material was from a non-vendor specific database [4]. A direct measurement of the relative delay could be done by sending the three pulses (248, 372, and 744nm) through the glass to improve the measurement.

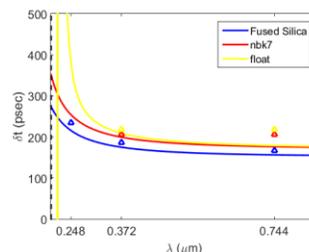


Figure 8: Setup used to measure the absolute delay.

CONCLUSION

The analysis presented shows that a refractive optical transport line (OTL) can achieve low time dispersion by following two recommendations: (1) Use low group velocity dispersion glass, MgF₂ and CaF₂ are best, and operate at the upper end of the visible spectrum [700-850nm]. Future work will include the quantum efficiency of the streak camera photocathode.

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