CookieBox White Paper

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Abstract

This document summarizes back of the envelope calculations and SIMION simulations defining the design space of the Cookie Box. We analyze linear time of flight spectrometers as well as hemispherical analyzers.

1 Mission

The CookieBox will provide angle and energy information of streaked photoelectrons sufficient for ptychographic reconstruction of the SASE substructure of one and two color pulses from the LCLS-II. This information must be provided with as high a rep-rate as possible.

2 Space Constraints

The CookieBox must fit into the beamline layout of the TMO hutch. The beamline is bounded by the floor, $1.2m$ below the beamline, and by the adjacent SXR beamline which is approximately a meter away horizontally in the plane containing the beam propagation directions of both beamlines. Free space exists above and to one side of the CookieBox. Space permits for the radial length to be as large as $1m$. In the propagation direction, space is much more limited, and the design should be as compact as possible. More information is needed on the space constraints in this direction.

However, size is limited by the functionality of the TMO space. The machine itself will be removed and replaced at points, and a maximally sized machine of $\simeq 2m$ diameter will be unwieldy.

The FEE CookieBox must fit in a more constrained space. The maximum radial extent is .6 meters.

3 Angular Streaking Reconstruction Constraints

In order to reconstruct the FEL SASE substructure, the CookieBox must resolve electrons to .25eV over a 100eV window with angular information over 360

degrees. Reconstruction is still robust with angular bins as large as 22.5^o (16 bins).

The photoelectrons to be streaked are born with a $cos^2[\theta]$ distribution and with a presumed energy of $330eV$. The electrons are streaked by $50eV$ and fall in the energy range $E_i = [280, 380]$.

Additionally, the $1MHz$ rate of the FEL imposes a maximum flight time of approximately $1\mu s$. While this can be extended by the length of the shortest flight time of electrons born in the previous bunch, this is not advisable as there is potential for crosstalk between shots.

4 Time of Flight (ToF) Analysis

The traditional CookieBox design has been a radial array of 16 ToF electron energy analyzers. These function by decelerating and focusing the electrons into a drift tube where they are eventually collected by an MCP. In this way time of flight is mapped to energy. Specifying the initial energy as E and retarded energy as E_{ret}, the initial free drift as r_o, the decelerating length as d_a, the time spent in region r_o and d_a as t_a, the deceleration as a, the time in the drift tube as t_d, and the drift tube distance as d_d, we can write:

$$t_a + t_d = \frac{r_o}{\sqrt{2E/m}} + \frac{2 * d_a}{\sqrt{2E/m} + \sqrt{2E_{ret}/m}} + \frac{d_d}{\sqrt{2E_{ret}/m}}. \tag{1}$$

If we assume that the deceleration, a, is large, then we can drop the t_a terms as a first approximation:

$$t_d = \frac{d_d}{\sqrt{2E/m}}, \tag{2}$$

and solve for E in terms of t_d

$$E = \frac{m * d_d^2}{2t_d^2}. \tag{3}$$

Now we assume there is some small error so that $t_d = t - \Delta t$ such that:

$$E = \frac{m * d_d^2}{2t^2} \frac{1}{(1 - \Delta t/t)^2}. \tag{4}$$

Taylor expansion keeping only the first term gives

$$E = \frac{m * d_d^2}{2t^2}(1 + 2\Delta t/t) = E_o(1 + 2\Delta t/t). \tag{5}$$

The error in energy is then

$$\Delta E = E_o * (2\Delta t/t). \tag{6}$$

This immediately yields a minimum length of the ToF design if the maximum upper bound of Δt is known. Setting this upper bound is the subject of the next subsection.

4.1 Time Uncertainty

There are three primary contributions to the time uncertainty in the ToF; the spatial extent of the photoionization, the difference in path length for equal energy electrons (electrostatic lens dispersion), and the response time of the MCP/anode readout. For argument, let us assume a flight tube of $500mm$ through which an electron of $100eV$ will travel in approximately $100ns$.

To begin with, we can confidently say that $50ps$ of time uncertainty in the MCP/anode readout can be achieved by the use of digitizers and peak processing. It should be noted that the anode readout spread as quoted by the manufacturer is $450ps$ and the timing resolution is dependent on our ability to extract peak positions from the pile-up signal.

The spatial extent of the photoionization is determined by the position of the focus and by the original energy of the photoelectrons. When the CookieBox is in dedicated use, we expect less than $10\mu m$ spot size. Assuming $280eV$ photoelectrons to find the maximum transit time of the focus, we find a $1ps$ transit time. Therefore, for small foci we can safely neglect the error from ionization volume. Conversely, when the CookieBox is used for pulse characterization in service to another experiment, we expect the focus size to be on the order of $1mm$. With 280eV photoelectrons this translates to 100ps.

The time dispersion of mono-energetic electrons is somewhat hard to estimate and depends upon the initial angular acceptance and lens systems. In the ideal scenario with no lensing or magnetic field distortions, the path length to a flat MCP (assuming curved mesh components for optimal fields) is modified by $\Delta d = sin(\theta)R_{mcp}$, where R_{mcp} is the radius of the MCP. The energy error can again be calculated starting from

$$t_d = \frac{d_d + \Delta d}{\sqrt{2E/m}} \tag{7}$$

and ending with

$$\Delta E = E * (2\Delta d/d_d) = E * (2R_{mcp}^2/d_d^2), \tag{8}$$

with the assumption $sin(\theta) = R_{mcp}/d_d$. The path length difference for a $d = 500mm$ and $R_{mcp} = 12.5mm$ is $310\mu m$ corresponding to an error of $E * 6.25e^{-4}$. For 100eV photoelectrons $310\mu m$ path length difference translates to a time uncertainty of $50ps$.

4.2 Design Prototype

If we assume a small focus size (near zero error from photoionization), the analytical form of the energy error is

$$\Delta E = 2 * E * \sqrt{\left(\frac{R_{mcp}^2}{d_d^2}\right)^2 + \left(\frac{\Delta t_{mcp}}{t}\right)^2} \tag{9}$$

$$= 2 * E * \sqrt{\left(\frac{R_{mcp}^2}{d_d^2}\right)^2 + \frac{2E}{m_e}\left(\frac{\Delta t_{mcp}}{d_d}\right)^2}. \tag{10}$$

By inserting constants as outlined in the previous subsection ($\Delta t_{mcp} = 50ps$ and $R_{mcp} = 12.5mm$) and assuming the maximal electron energy of $100eV$, the numerical relation between energy resolution and drift length can be plotted as in figure 2. The energy resolution is shown for a perfect ToF in blue, for a Tof with additional path length deviation of .05% equivalent to 50ps in orange, and for operation with a $1mm$ spot size in green. The radial angular acceptance as a function of distance is shown in the bottom plot of figure 2.

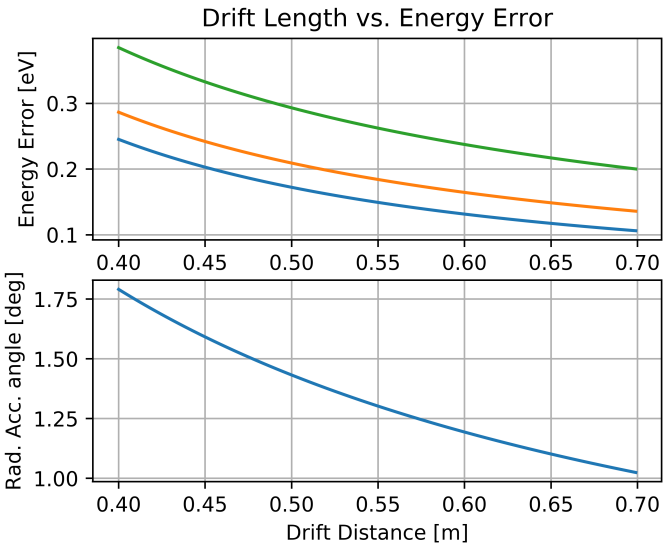

Figure 1: Top: energy error as a function of ToF drift lenght for the ideal case (blue), additional $50ps$ time error (orange) and for ideal with a 1mm spot size (green). Bottom: radial collection half angle of the ideal ToF.

The graphs suggest that half meter length drift regions are sufficient for achieving $.25eV$ resolution with a margin of error of $.04eV$. However, the angular collection efficiency of the perfect ToF design is very low. The general consensus is that 16 ToF detectors provides a good balance between cost and angular

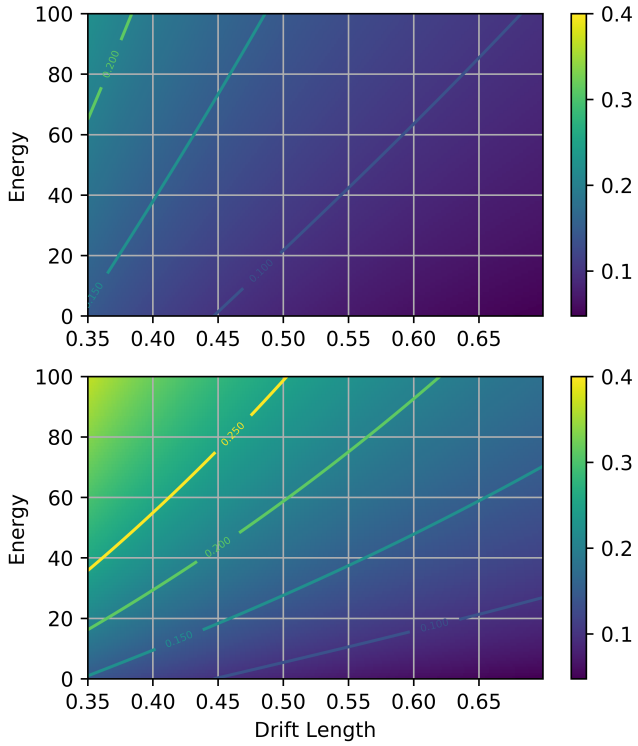

Figure 2: Energy error as a function of ToF drift lenght for $50ps$ (top) and $100ps$ (bottom) time error.

information required for ptychographic reconstruction. An array of 16 "ideal" ToFs, the total radial (ϕ) angular acceptance at $500mm$ drift lenght is 23 degrees, but much less in the axial (theta) angle. Assuming a cos^2 distribution of the initial photoelectrons, the ToFs will collectively capture approximately .64% of the total distribution - a collection efficiency likely too low for coincidence experiments even with the 1MHz rep-rate of the LCLS-II.

5 Simion Simulations

To increase collection efficiency, lens systems can be employed. Given the ratio of the energy window to total energy, chromatic aberration in the ion lens optics is severe and unavoidable. It is impossible to adequately focus electrons at the high end of the range without completely diverging electrons on the low end.

Therefore, a simple lens system can only hope to focus low energy electrons. There is one workaround to this reality. After the drift tube, electrons are already separated in time and an accelerating lens system focusing onto the MCP can increase collection efficiency albeit at the expense of energy resolution.

Simulations have been conducted in SIMION to measure the energy efficiency and collection angle of a such a scheme and are shown in figure 3 for a $600mm$ ToF with a full radial angular collection (using a $25mm$ diameter detector) of 2.4^o degrees. A single ToF is simulated and is constructed of an initial curved mesh followed by a flat mesh separating the deceleration region from the drift tube, and a third mesh in front of the MCP. A lensing field prior to the drift tube and the addition of the post drift collection increases the angular collection to as large as 10 degrees. The ragged nature of the simulation data suggests that the simulation is having trouble handling some electron trajectories. The

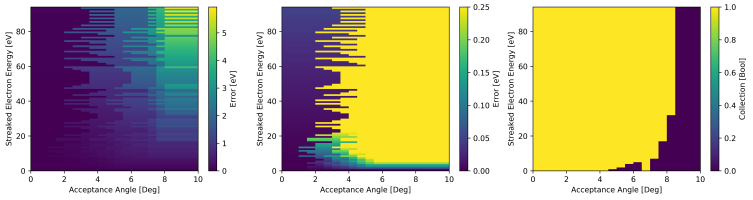

Figure 3: SINION simulation results for energy error as a function of electron energy and total acceptance angle for a $600mm$ long ToF. Left: error for the full acceptance angle under test. Middle: same as left but the energy error has been clipped at $.25eV$. Right: collection boolean showing collection, 1, or a miss 0.

left most plot of figure 3 shows the full energy resolution range, which degrades to as great as $5eV$ at the full acceptance angle of 8^o degrees. The central plot in figure 3 is the same as the left plot except for that the energy scale has been truncated at $.25eV$ to highlight the design criteria energy resolution. The right most edge of the jagged region most probably represents the real energy resolution – better simulation and more introspection are required. The right most plot of figure 3 shows the collection boolean for electrons of particular energy and angle. High energy electrons are collected with up to 8^o degrees while low energy electrons suffer from divergent lensing. The total collection efficiency of 16 ToF on a $cos^2[\theta]$ distribution is plotted in figure 4. Collection efficiency is nearly 20% at 8^o, which is more than enough to satisfy coincidence experiments.

5.1 Multiplexing

The simulation results above demonstrate that larger collection efficiency can be obtained using lens systems while retaining good electron energy resolution for high energy electrons. With 16 spectrometers there is believed to be an overabundance of angular information. Therefore, the spectrometers can be

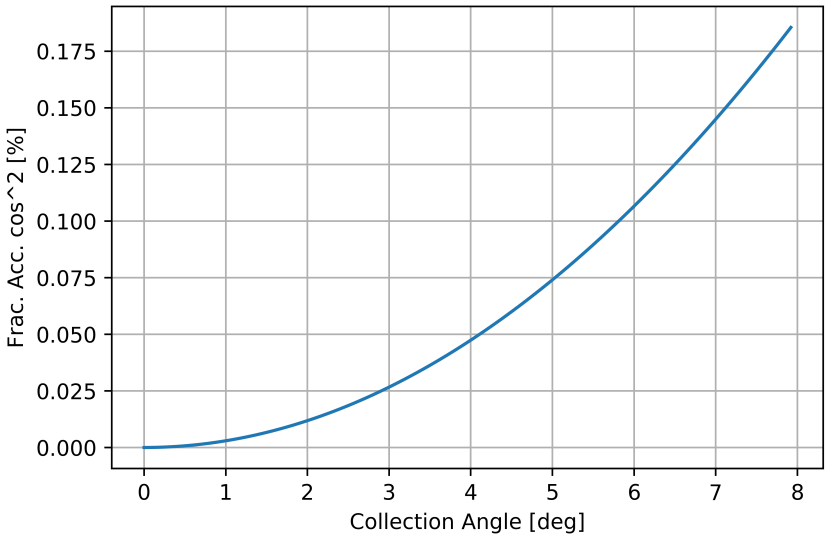

Figure 4: Collection efficiency for a $600mm$ long ToF assuming a cos^2 distribution.

run with different retarding potentials to target different energy ranges of the photoelectron distribution. With such a scheme, high angular acceptance with adequate energy resolution can be made available for coincidence streaking experiments.