A Single Electron Detection Setup for Transverse Diagnostics at FLASHForward

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Abstract

The FLASHForward project at DESY is a plasma-wakefield acceleration experiment in which the aims are to produce, in a few centimeters of ionized gas, beams of GeV energy with high quality, develop diagnostics for such beams, and evaluate their application in the fields of high energy physics and future compact light sources. Several conventional as well as novel diagnostics tools, capable of characterizing ultra-short plasma-wakefield accelerator beams are under development. Notably, the Femtosecond innovative RelativistiC Electron (FiRCE) probe which can be used at the location of plasma. This probe may improve our understanding of the trapping and acceleration processes in plasma-wakefield accelerators. For such diagnostics, there is ultimately a need for single electron detection setup. In this report, few of the characteristics of this detection set up is discussed.

Contents

1. Introduction

Interest in compact high energy particle accelerators has greatly increased the interest in the process of plasma wakefield acceleration over the last decades. A plasma wakefields accelerator (PWA) can deliver accelerating fields that are approximately a 10-100 times higher than those in conventional radiofrequency (RF) or superconducting RF cavities, which has opened a transformative path towards novel compact accelerators. Today, most major large-scale particle accelerator laboratories, such as BNL, CERN, DESY, LBNL, SLAC, have initiated and/or are running research and development programmes that focus on the PWA process. There are two major approaches for the excitation of plasma wakes: the Laser-driven Wakefield acceleration and (LWFA) and particle-driven Plasma-WakeField Acceleration (PWFA). In LWFA, a high-intensity laser pulse with a typical duration of tens of fs ionizes gas to plasma and drives the wake, while in PWFA a high-current electron beam is the driver in a plasma. For this report, we will limit the discussion to PWFAs. The FLASHForward project at DESY is a pioneering plasma-wakefield acceleration experiment that aims to produce, in a few centimeters of ionized hydrogen, beams with the energy of order GeV that and with sufficient quality for applications in high energy physics and to demonstrate free-electron laser (FEL) gain. The plasma can be created by ionizing a gas in a gas cell with a multi-terawatt (TW) laser system or via discharge mechanism. The plasma wave will be driven by high-current-density electron beams from the FLASH linear accelerator. The laser system can also be used to provide optical diagnostics for both the plasma and electron beam since a the <30 fs synchronization between the laser and the driving electron beam has been achieved [1]. The charge-density perturbation, established in the wake of the driver, results in strong electric fields on the order of 10 GV/m, depending on the plasma and the driver properties. In June of 2018, FLASHForward team successfully generated a wakefield in plasma with a field strength of more than 12 GeV/m by means of an electron beam from the FLASH accelerator. This is the first time in Europe, and the second time ever, that such a high gradient has been generated by an electron beam as the "driver beam". Now the experimental focus of the project is on the acceleration of "witness" electron beams in such high gradient fields [2].

2. Wakefields in The Plasma

Wakefields in plasmas are generated by a driver, which in our discussions is a charged particle beam which creates a charge-density "wake" in a plasma. As plasmas are not bound by material breakdown limits, these wakes can have enormous accelerating gradients. The high gradient "wake", or the accelerating structure (bubble) formed in plasma, will depend on the relative charge density of the driver beam to the background plasma. When the driver beam relative charge density is low. The force of the beam driver is not high enough to expel all the electrons from the accelerating bubble and the resultant wake is more or less of a sinusoidal form (linear regime). When the driver beam relative charge density is high, all the electron will be ejected from the bubble and a pure ion channel is formed. The wakes, in this case, which is also known as the Blowout regieme, have a sawtooth form. For very high relative charge density the driver can produce sawtooth waves with steep nonlinear rises and falls. The longitudinal electric fields associated with the wake is then able to accelerate relativistic particles injected into the plasma or even, if its amplitude is large enough, to trap particles from the plasma itself. By surfing on this electrostatic wave, particles can be boosted to high energies over very short distances. In Figure 1 the wake created by an electron beam in plasma is shown.

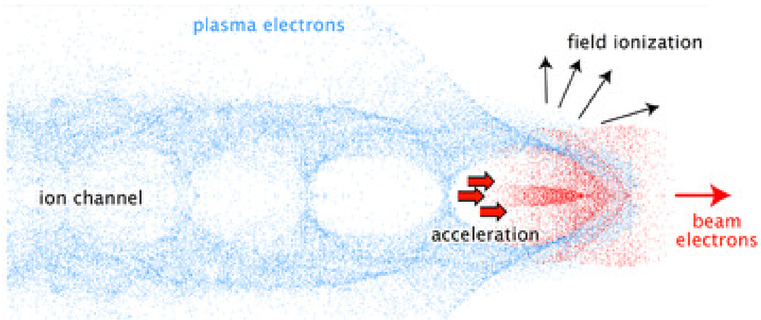

Figure 1: Wake generated by an electron beam in a plasma

3. Beamloading and Injection Mechanisms

In order for the quality of the accelerating witness beam to be or remain high, the modification of the plasma structure due to the presence of the witness beam must be small. This is typically achieved by beamloading where the witness of quantified charge is shaped and strategically placed in the back of the wake produced by the driver and so that it can extract energy with high efficiency, low energy spread, and prevent emittance degradation.

3.1. External Injection

External injection is one of the pioneering PWFA setups. It is a two-bunch scheme, in which a plasma wake is set up by one electron beam and the witnessed electron beam are accelerated if they are in the right phase with respect to the wake. The witness and drive beam can be produced from a single beam by means of a scraper [3], or can be produced and shaped independently via velocity bunching. The driver electron beam continuously loses energy due to the deceleration in the plasma, while the electrons of the witness beam gain energy. Placement, charge, and shape of the witness beam can be determined via the theory of beamloading in the nonlinear plasma wakefield. However, diagnostics at the location of the plasma that can detect the Electric field of the wake and electron beam will not only improve our understanding of the process but also allow for optimization of this process.

3.2. Internal Injection

One of the scientific goals of the FLASHForward experiment is to demonstrate and develop a plasma cathode. For such experiment, the witness beam are trapped and accelerated electrons from the background plasma. The density-downramp (DDR) injection scheme is the planned internal injection mechanism for the new future since it is one of the most promising concepts in beam-driven plasma wakefield accelerators for the generation of high-quality witness beams. The main idea of the DDR injection method is that the plasma electron can become trapped in the plasma wake if it propagates equal or faster phase velocity at the phase position of the electron. It turned out, that the trapping of electrons much easier achievable in the blowout regime. The tunability of this method makes it attractive to use in the FLASHForward experiment since it requires short pulse length and low emittance, which can be controlled by the steepness of the ramp. The amount of trapped charge also depends both on the density difference and on the steepness of the ramp. Availability of a transverse diagnostic probe at the location of the plasma is also advantageous in this scheme.

4. FiRCE Transverse Beam Diagnostics

Table 1: FLASH2 and Predicted FLASHForward Beam Parameters

Parameter	Driver	Witness
E (GeV)	0.4-1.25	$\sim 1.6 - 2.0/>1.6$
$\Delta_{\mathrm{E}}(\%)$	~ 0.1	0.3-0.5 / ~ 0.2
$\epsilon_{\mathrm{n}}(mm - mrad)$	>1	0.1-0.5 / ~ 2
I_{p}(kA)	1-2.5	$\sim 0.5 - 1.0/ \sim 2$
$\sigma_{\mathrm{b}}(fs)$	50-500	$\sim 20 - 40/ \sim 10 - 80$

The FiRCE probe uses a few femtosecond long relativistic electron bunches to probe the wake produced in a plasma. The electric field of the accelerating structure can deflect the probe electron bunch traversing the wake, which then experiences a momentum modulation induced by the electric field of the wake. This modulation causes a density variation in the probe beam which is recorded after some free-space propagation. This variation of density produces a snapshot that can reproduce many of the wake structure information and its evolution. Based on the parameters in Table 1 and recent simulation studies, the recording of this snapshot must be done by a carefully planned single electron detection set up [4].

5. Research Description

In order to suppress the coherence effects due to microbunching instabilities in high-brightness electron beams at XFEL, use of scintillation screens instead of transition radiation screens have been studied. These inorganic scintillators have good radiation resistance, high stopping power for high light yield, and short decay times of the excited atomic levels. One of such scintillators also provided the required spatial resolution for the FiRCE probe. In this report, we will discuss the performed studies on the scintillator's effect and role in the detection mechanism. Design of the optics and the optimized geometry will not be discussed in detail and is part of the future work.

6. Theoretical Foundation

In this section, the brief description of the research goal is given. This study includes two stages: first, the beam divergence due to its self-potential when it's passing through a slit, and second - the interaction of this beam with an LYSO scintillator material. Both analyses are important for the calibration of the detector/Camera data and determining the electron beam parameters. In Figure 2 one can see the simplified scheme of the beam image observation setup. The equations and theoretical specification used in this work are provided next.

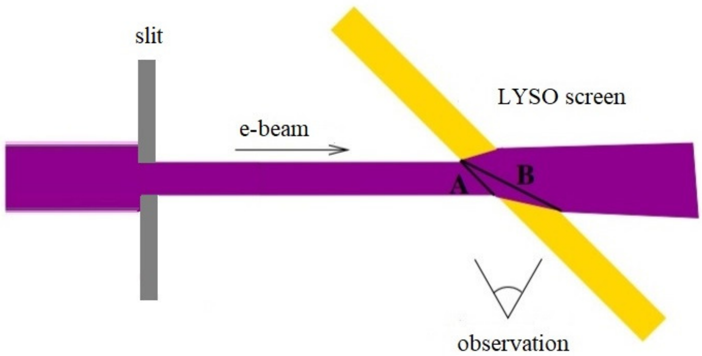

Figure 2: Layout to image fluorescent light onto a detector [5]

6.1. Electron Beam Divergence

When modeling the propagation of a charged particle beam at a high current, the electric field due to the space charge of the beam significantly affects the trajectories of the charged particles. Perturbations to these trajectories, in turn, affect the space charge distribution. In order to accurately predict the properties of the beam, the particle trajectories and fields must be computed in a self-consistent manner. When the magnitude of the beam current is large enough that Coulomb interactions are significant, the shape of the beam may be determined by solving a set of strongly coupled equations for the beam potential and the electron trajectories,

$$\nabla \varepsilon_0 \nabla V = \sum_{i=1}^{N} e\delta(r - q_{\mathrm{i}}) \tag{1}$$

$$\frac{d}{dt}(m_{\mathrm{e}} v) = e\nabla V \tag{2}$$

6.2. Scintillation Effects

Luminescence centers in crystal structures are responsible for scintillation. These centers either have an intrinsic origin or are created as wanted or unwanted impurities in the lattice structure. Accordingly, the crystals are classified as intrinsic or extrinsic scintillators. There is a third category in between these classes - inorganic scintillators, which consists of the self-activated crystals or scintillators. Passing through matter electron losses energy on ionization and bremsstrahlung. While ionization loss increases logarithmically with energy, bremsstrahlung losses rise nearly linearly (fractional loss is nearly independent of energy), and dominates above the critical energy (where the ionization and bremsstrahlung cross sections are equal), a few tens of MeV in most materials. These electron energy losses are given by [6],

$$\left\langle \frac{-dE}{dx} \right\rangle = \frac{1}{2}\frac{K}{Z}\frac{1}{\beta^2}\left[\frac{\log m_{\mathrm{e}}c^2\beta^2\gamma^2(m_{\mathrm{e}}c^2(\gamma-1)/2)}{I^2} + \right.$$
$$\left. +(1-\beta^2) - \frac{(2\gamma-1)}{\gamma^2}\log 2 + \frac{1}{2}\frac{(\gamma-1)}{\gamma^2} - \delta\right) \tag{3}$$

Apart from properties of the incident electron, some properties of the scintillating medium such as its density and thickness have a major impact on the deposited energy or the total stopping power. The total stopping power comprises of collision and radiative stopping powers. The collision stopping power is the rate of the energy loss due to Coulomb collisions which result in the ionization and excitation of atoms, while radiative stopping power, which is dominant at higher energies, is due to collisions with atoms and atomic electrons in which bremsstrahlung photons are emitted. If we define the angle of scattering as θ_0:

$$\theta_0 = \frac{13.6 MeV}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \log x/X_0] \tag{4}$$

Here p, βc, and z are the momentum, velocity, and charge number of the incident particle, and $x/X_0$is the thickness of the scattering medium in radiation length.
A comprehensive analysis of different scintillation screens was done in [7, 8]. This result confirms that LYSO is a suitable material for beam profile measurements and LYSO-screen is planned to be used at FLASHForward facility. The main properties of the LYSO screen are listed in Table 2.

Table 2: LYSO screen properties

Chemical formula	$Lu_{1.8}Y_{.2}SiO_5$:Ce
Index of Refraction	1.81
Wavelength of peak emission	420 [nm]
Density of the scintillator material	7.1 [g/cm3]
Light yield	30000 [photons/MeV]
Decay time	45 [ns]
Scintillation efficiency (compare to NaI)	75

7. Results and Discussions

The electron beam passage through the slit was mainly studied via Comsol Multiphysics software[9] while passage through the LYSO was studied in the optical raytracing code ZEMAX [10]

7.1. Electron Beam Divergence

This part of the model computes the properties of an electron beam as it propagates through the free space, passes through the slit, then through the free space again until it reached the LYSO. The output of interest is the number of particles arriving at the scintillator and the resultant photons. The geometry of the model includes a tube of vacuum with a diameter few times the transverse size of the beam, the slit, and the scintillator. The slit is located at 0.2 m from the inlet beam point. Distance from the slit to scintillator was chosen as 0.3 m. Parameters of the beam were taken from the studies in [4], in agreement with FLASH main (Table 1) and probe beam parameters. The geometry and particle tracing in the tube are shown in Figure 3.
Diffraction effects due to electron beam passage through the slit were also estimated using the python code for future parameter scan studies of the single electron detection set up. This code is attached in Appendix. Taking the resulting beam divergence and the number of electrons arriving at the scintillator, we can then model the LYSO effect as described next to evaluate the final size of the beam on the back of the LYSO (for the simplest case which would be for a camera placed directly after the scintillator). Particle trajectories are shown in Figure 4.

7.2. Scintillation Effects in LYSO

To simulate the electron - matter interaction the value of stopping power for electrons in LYSO is needed. The data for total stopping power was taken from [11]. In Figure 6 one can see these values for the electrons with varying energies.
To estimate the light emission in crystal the calculation of deposited energy for the electrons in LYSO was made in Comsol Multiphysics software[9]. The model considers electrons with initial energy 42.5, 50, 57.5 MeV (assuming an electron probe beam of 50

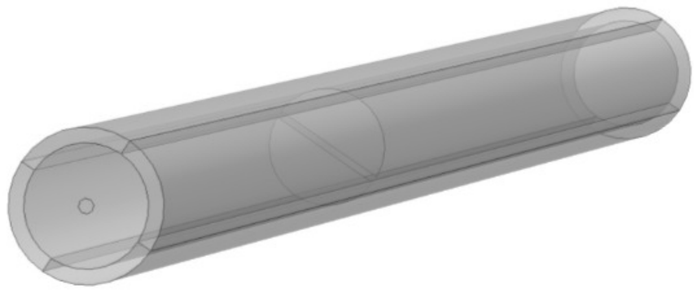

Figure 3: Geometry used in Comsol model

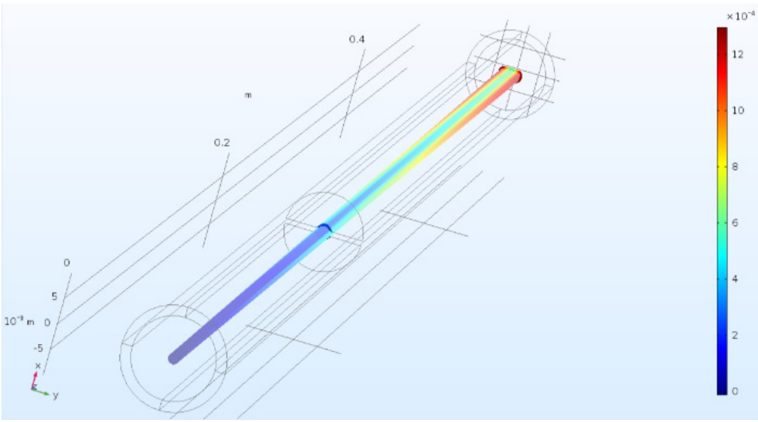

Figure 4: Particle tracing through the slit

MeV with 15 percent energy spread) passing through the LYSO material with properties, mentioned in 2. The Particle-Matter interaction was model as described above and uses the stopping powers from data presented in Figure 6. Results are provided in Figures[4-6].

To study the beam profile monitor resolution and its dependence on geometry of the set up, the response of the system to a point source was investigated in detail. Simulations have been performed with the optical raytracing code ZEMAX. The geometry used for simulation is shown in Figure 2. Optical transition radiation, generated by the electron is emitted toward the camera. Considering a single electron as a point source which deposits energy in scintillator material, light is emitted along its passage inside the material. The emission distribution on the exit surface of the scintillator is viewed by the monitor and the RMS size of the distribution is taken as the scintillator resolution.

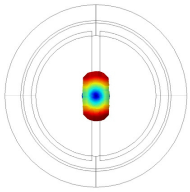

Figure 5: Particles reaching the scintillator

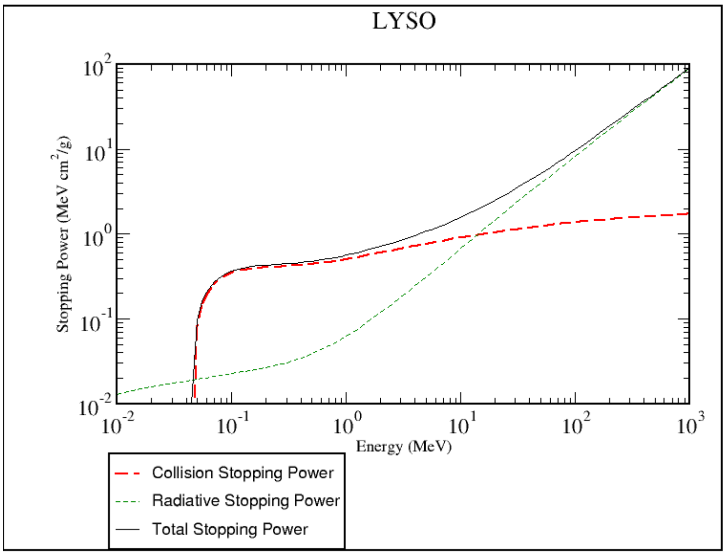

Figure 6: Stopping power for different energies in LYSO crystal

Based on the studies presented in [8] we expect to find the best angle for the setup. Since LYSO has a high refractive index the contribution of total reflection is very large. The point spread function of electron was evaluated for the different incline angles of scintillator which are shown in Figure 10. The main cause for the existing inconsistency in the beam size is the diversity of the transmission factor and the collection efficiency for each individual setup. The collection efficiency of the optical system influences the spot size and consequently the resolution. Despite several studies, it was not possible to see the expected result based on the [8] which is study of another similar scintollator material and no optimized angle for the final geometry of the set up was found. After more research and discussion with the experts it was concluded that the capabilities of the licensed ZIMAX software were different than that of the version used in the 2012 research.

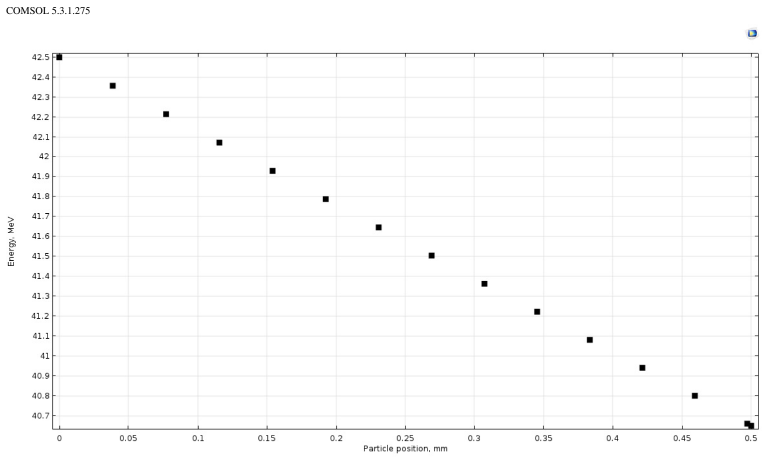

Figure 7: Stopping power for different electrons with the initial energy 42.5 MeV in LYSO crystal

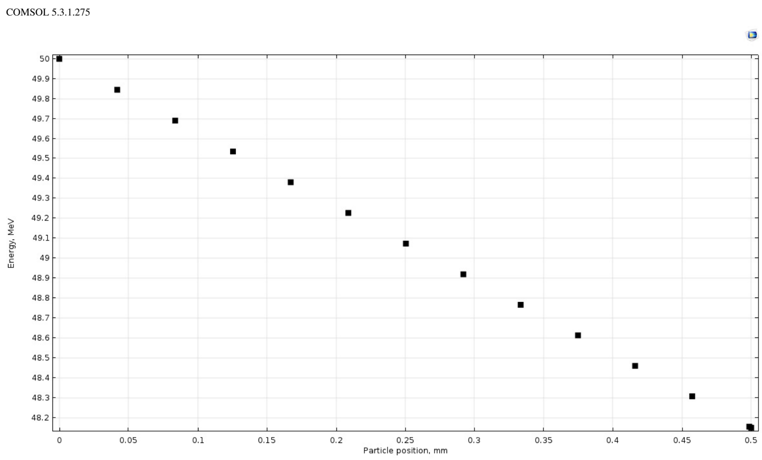

Figure 8: Stopping power for different electrons with the initial energy 50 MeV in LYSO crystal

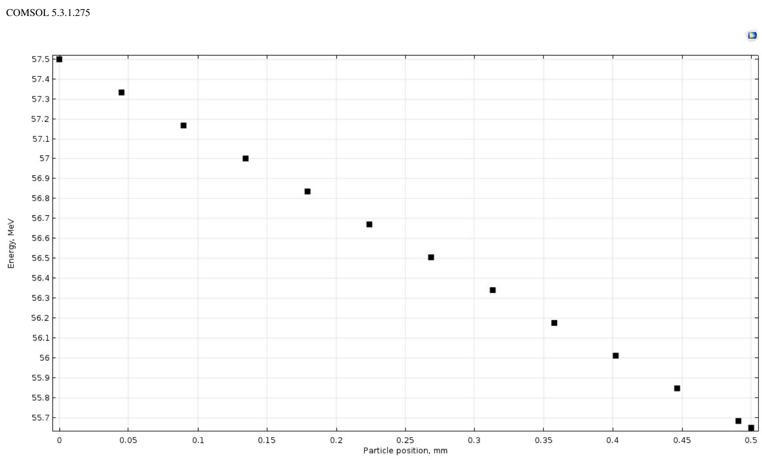

Figure 9: Stopping power for different electrons with the initial energy 57.5 MeV in LYSO crystal

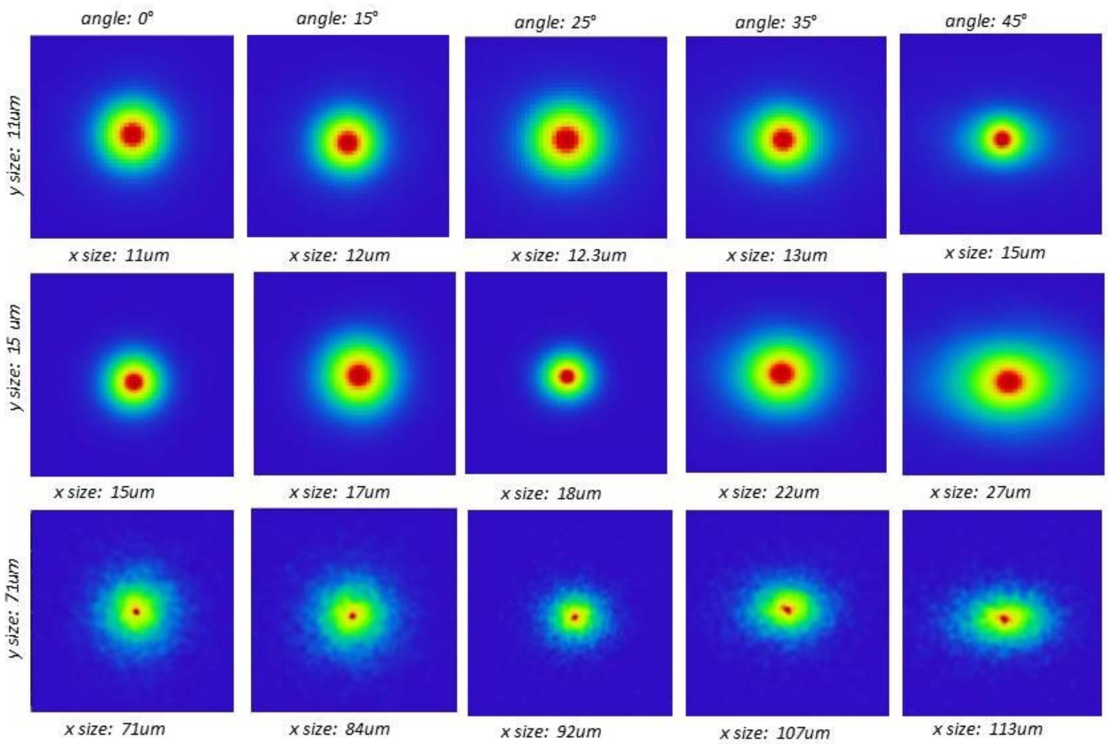

Figure 10: Point spread functions for different thicknesses of LYSO crystal and few angles of incidence.

8. Next Steps

This work should be expanded to obtain the results which can be used in the experiment. The ray tracing setup model must be evaluated in a version of ZEMAX allowing for internal reflection in different layers of the LYSO so that the effects in close agreement of what was provided in [8] are seen and an optimized angle is determined. However, the current ZEMAX model does not assume the observation equipment such as a CCD camera and to get the realistic result the final set up geometry must be considered in the model. Also, only single electron detection was studied, to complete the research it is necessary to investigate the whole beam interaction with the scintillator material. The python diffraction code can be amended and used with the ray tracing model to optimized the complete single electron detection setup.

A. Python code to calculate the diffraction effects

```
import numpy as np
import random
def wavefront_initialize(pixelsize_x,pixelsize_y,npixels_x,npixels_y,
amplitude_value):
    amplitude = np.zeros((npixels_x,npixels_y))
    amplitude += amplitude_value
    p_i_x = np.arange(npixels_x) * pixelsize_y
    p_x = (p_i_x - 0.5 * (p_i_x[-1] - p_i_x[0]) )
    p_i_y = np.arange(npixels_y) * pixelsize_y
    p_y = (p_i_y - 0.5 * (p_i_y[-1] - p_i_y[0]) )
    return p_x,p_y,amplitude
def wavefront_aperture(p_x,p_y,amplitude,diameter=40e-6):
    p_xx = p_x[:, np.newaxis]
    p_yy = p_y[np.newaxis, :]
    filter = np.zeros_like(amplitude)
    sigma = diameter/2.35
    rho2 = p_xx**2 + p_yy**2
    filter = np.sqrt(np.exp(-rho2/2/sigma**2))
    filter = np.exp((-rho2/2/sigma**2) + ( 1j * wavenumber * rho2))
    return p_x,p_y,amplitude*filter
def propagator2d(x,y,z,method="fourier_convolution",
wavelength =1e-15,propagation_distance=1.0,return_angles=0):
    from timeit import default_timer as timer
    t_start = timer()
    if method == "fraunhofer":
        x1,y1,z1 = propagator2d_fraunhoffer(x,y,z,wavelength=wavelength)
        if return_angles:
            pass
        else:
            x1 *= propagation_distance
            y1 *= propagation_distance
    elif method == "fourier_convolution":
        x1,y1,z1 = propagator2d_fourier_convolution(x,y,z,
        propagation_distance=propagation_distance,
        wavelength=wavelength)
        if return_angles:
            x1 /= propagation_distance
            y1 /= propagation_distance
    t_end = timer()
    return x1,y1,z1
def propagator2d_fourier_convolution(p_x,p_y,image,propagation_distance,
```

```
wavelength):
    fft = np.fft.fft2(image)
    # frequency for axis 1
    pixelsize = p_x[1] - p_x[0]
    npixels = p_x.size
    freq_nyquist = 0.5/pixelsize
    freq_n = np.linspace(-1.0,1.0,npixels)
    freq_x = freq_n * freq_nyquis
    # frequency for axis 2
    pixelsize = p_y[1] - p_y[0]
    npixels = p_y.size
    freq_nyquist = 0.5/pixelsize
    freq_n = np.linspace(-1.0,1.0,npixels)
    freq_y = freq_n * freq_nyquist
    freq_xy = np.array(np.meshgrid(freq_y,freq_x))
    fft *= np.exp((-1.0j) * np.pi * wavelength * propagation_distance *
            np.fft.fftshift(freq_xy[0]*freq_xy[0] +
            freq_xy[1]*freq_xy[1]) )
    ifft = np.fft.ifft2(fft)
    return p_x.copy(),p_y.copy(),ifft
def propagator2d_fraunhoffer(p_x,p_y,image,wavelength):
    #compute Fourier transform
    F1 = np.fft.fft2(image)
    F2 = np.fft.fftshift( F1 )
    # frequency for axis 1
    pixelsize = p_x[1] - p_x[0]
    npixels = p_x.size
    freq_nyquist = 0.5/pixelsize
    freq_n = np.linspace(-1.0,1.0,npixels)
    freq_x = freq_n * freq_nyquist
    # frequency for axis 2
    pixelsize = p_y[1] - p_y[0]
    npixels = p_y.size
    freq_nyquist = 0.5/pixelsize
    freq_n = np.linspace(-1.0,1.0,npixels)
    freq_y = freq_n * freq_nyquist
    return freq_x,freq_y,F2
def plot_show():
    import matplotlib.pylab as plt
    plt.show()
def plot_image(mymode,theta,psi,title="TITLE",xtitle=r"X [$\mu m$]",
ytitle=r"Y [$\mu m$]",cmap=None,show=1):
    import matplotlib.pylab as plt
    fig = plt.figure()
```

```
    plt.imshow(mymode.T, origin='lower', extent=[theta[0],
    theta[-1],psi[0],psi[-1]],cmap=cmap)
    plt.colorbar()
    ax = fig.gca()
    ax.set_xlabel(xtitle)
    ax.set_ylabel(ytitle)
    plt.title(title)
    if show: plt.show()
def theoretical_profile(p_x, p_y, wavelength):
    from scipy.special import jv
    x = (2*np.pi/wavelength) * (aperture_diameter/2) * p_x
    y = (2*np.pi/wavelength) * (aperture_diameter/2) * p_y
    U_vs_theta_x = 2*jv(1,x)/x
    U_vs_theta_y = 2*jv(1,y)/y
    I_vs_theta_x = U_vs_theta_x**2
    I_vs_theta_y = U_vs_theta_y**2
    return I_vs_theta_x, I_vs_theta_y

if __name__ == "__main__":
    aperture_diameter = 11e-9
    aperture_type     = 2
    pixelsize_x = 1e-9
    pixelsize_y = pixelsize_x
    npixels_x =  1024
    npixels_y =  npixels_x
    propagation_distance = 0.5
    beam_size = 0.5e-6
    slit_distance = 0.5
    method = "fourier_convolution"
    #method = "fraunhofer"
    mean = 50 #energy in MeV
    std_dev = 3
    kinetic_energy = int(random.normalvariate(mean, std_dev))
    h = 6.5821e-22  #Planks constant in MeV*sec
    c = 299792458
    wavelength = h*c/kinetic_energy  #De broglie wavelenght of the e
    wavenumber = 2 * np.pi / wavelength
    p_x,p_y,amplitude = wavefront_initialize(pixelsize_x,pixelsize_y,
    npixels_x,npixels_y,amplitude_value=1.0)
    p_x,p_y,amplitude = wavefront_aperture(p_x,p_y,amplitude,
    diameter = beam_size)
    angle_x,angle_y,amplitude_propagated propagator2d(p_x,p_y,
    amplitude,method=method,wavelength=wavelength,
    propagation_distance=slit_distance,return_angles=1)
```

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