Electron X-ray Transition RAdiation (EXTRA)

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1 Why we want to go DESY

When we first knew about Beam Line for School (BL4S), we were thrilled to join the competition and have the amazing opportunity to work as a team and represent our school. We are all extremely interested in Physics, a subject which stimulates our curiosity and will of knowledge. In the past years we have been taking part in the national project "Extreme Energy Events", in which we operate a cosmic ray muon telescope installed in our school. Visiting an accelerator facility like DESY and working in touch with high-energy physicists would be therefore an exciting opportunity for all of us.

We plan to study the transition radiation (TR) X-rays emitted by fast electrons, measuring the positions of TR X-rays with respect to the radiating electrons with the high-granularity MIMOSA pixel detector available at the DESY beam line facilities [1].

2 Experiment proposal

We aim to study the TR produced by fast electrons or positrons crossing a multilayer radiator. The DESY beam line is suitable for this measurement, as it provides pure electron or positron beams in the TB21 area (see Figure 1 and Ref. [1]).

TR can be emitted in the X-ray energy range when ultra-relativistic charged particles cross the interface of two media with different dielectric constants [2]. Since the probability of emitting a photon at each interface is small, radiators consisting of many foils with regularly spaced gaps are used.

The main properties of TR can be summarized as follows:

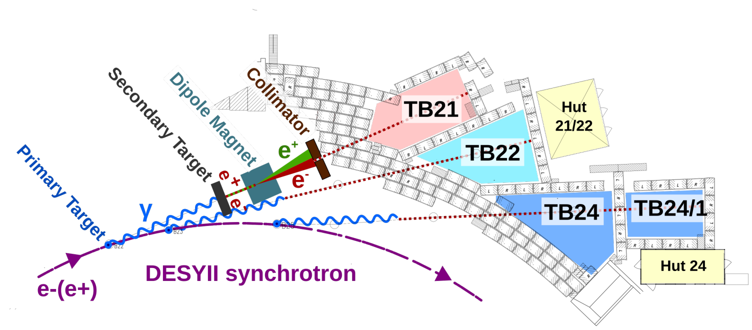

Figure 1: The DESY Beam Accelerator [1].

1. TR production starts when the Lorentz factor of the particle exceeds a threshold value $\gamma_{th} \approx 2.5 d_1 \omega_1$, where d_1 is the foil thickness in μm and ω_1 is the radiator material plasma frequency in eV units;

2. The average number of X-rays produced at each interface is $N_X = \alpha$, where $\alpha = 1/137$ is the fine structure constant.

3. The average energy of each X-ray is given by $< E_X >= 0.3\gamma_{th}\omega_1$;

4. The average emission angle of X-rays with respect to the particle is $\theta \sim 1/\gamma$, where γ is the Lorentz factor of the radiating particle [3, 4];

5. The yield of TR X-rays usually increases with the Lorentz factor up to $\gamma_{sat} \approx \gamma_{th}\sqrt{d_2/d_1}$ where d_2 is the spacing between the radiator foils.

As an example, if $d_1 = 20$ μm and the foils are made of polyethilene (ω_1=20 eV [5]), $\gamma_{th} = 500$ ($p_{electron} \sim 250$ MeV/c) and $< E_X >= 3keV$. If the air gaps are 200 $\mu m \div 2$ mm, saturation will occur at $\gamma_{sat} \approx (2 \div 5) \cdot 10^3$ ($p_{electron} \sim (1 \div 2.5)$ GeV/c).

The experimental setup consists of a radiator, a helium pipe, a set of six Monolithic Active Pixel Sensors (MAPS), and a halo detector (Fig. 2). Electrons crossing the radiator (fig. 3) will produce TR X-rays, that will be detected, together with electrons, by the MAPS. To ensure adequate separation between TR X-rays and the electron beam, the detector should be located 1-2 meters downstream the radiator [3]. To avoid absorption of X-rays in air, a pipe filled with helium should be placed between the radiator and the detector [6].

The TR X-rays and the electron beam will be detected by a set of six MAPS, equipped with Mimosa26 chips [7]. Since the chips are 50 μm thick, the absorption probability of 5 keV X-rays in a single chip is 94% [6], while the probability of absorption in any chip is close to 100%. Each chip has a cross section of 13.7×21.5 mm^2 and contains 576×1152 pixels of 18 μm side. The pixels work with a fast binary readout system, with a noise of about 14 equivalent electrons per channel [8] (i.e. about 50 eV in silicon), allowing the detection of soft X-rays.

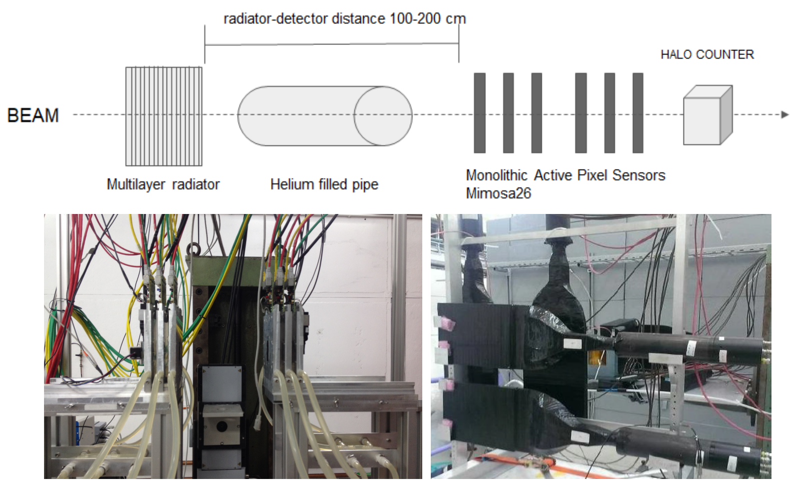

Figure 2: Top panel: Scheme of the experimental setup. The beam direction correspond to z-axis of the reference frame. Bottom left panel: Mimosa telescope. Bottom right panel: Halo counter.

The Mimosa chips can measure the positions of X-rays, but they are not able to determine their energies. However this is not an issue for our experiment, since we aim to detect the pattern of TR X-rays around the electron beam. The electron positions will be determined exploiting the measurements on all the chips (electrons are expected to release an ionization energy loss in each chip). Finally, the halo counter downstream will define a narrow beam, allowing the rejection of showering particles.

The data analysis will go through the following steps:

1. For each chip we will identify the fired pixels and we will group adjacent fired pixels into clusters;
2. We will search the clusters corresponding to the electron track with a linear fit of the track through the six chips;
3. The remaining clusters will be associated to possible TR X-rays;
4. For each X-ray cluster we will evaluate its position with respect to the cluster corresponding to the electron;
5. We will study the distributions of the positions of X-ray clusters.

We have written a Monte Carlo simulation of our experiment using Python 3 (see Appendix). We assume that the angles of production of TR X-rays are distributed according to the probability density function for single foil emission [3] (left panel of Fig. 4). The plot in the right panel of Fig. 4 shows the result of our simulation. The output of the Mimosa chip should match the simulated results, where the x-y plane portrays the chip pixels.

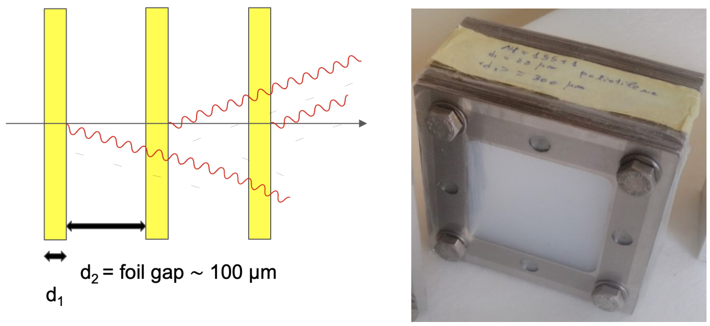

Figure 3: Left panel: Sketch of a multilayer radiator. Right panel: radiator module made of 155 polyethylene foils 25 μm thick and 300 μm of gap.

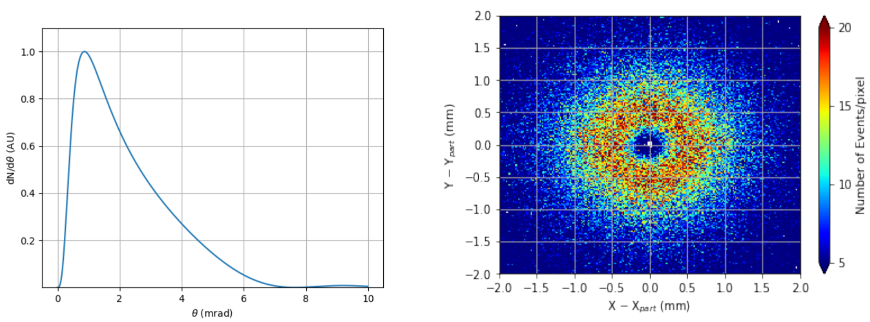

Figure 4: Left panel: Theoretical angular distribution of TR X-rays from a single foil. Right panel: MIMOSA chip simulated output. The relative positions of TR pixel (X-Y view) with respect the electron one are shown. The color scale indicates the number of events detected in each pixel. The white hole in the middle of the image shows the 4×4 masked pixels corresponding to the electron positions.

3 What we hope to take away

Throughout the preparation for the competition we have faced several challenges, which tested our skills, enabled us to deepen our knowledge of physics and our approach to the team work as well. Indeed, we have been involved in a real research activity which taught us the priceless value of everyone's contribution to a common project and how to support one each other. We are incredibly proud of our proposal and hope to perform our experiment at DESY and report our data next year.

4 Acknowledgements

We would like to thank our school for giving us the incredible opportunity to join this competition. Moreover, we feel very lucky for having Prof. M. F. Muscarella and Prof. S. Turbacci as wonderful and supporting teachers, as well as Prof. B. M. Fanti, I. Iusco and D. Ricchiuti, whose precious advice guided us through the project. Last but not least, we are grateful for our amazing friends from the Extreme Energy Events school team, who supported and assisted us in this tough period, giving us the emotional support which every scientist needs during an important work.

5 Appendix

The python code used for the TR simulation is reported here.

```python
import numpy as np
import matplotlib.pyplot as plt
from matplotlib import ticker, cm
import matplotlib.colors as colors

d1 = 20. # foil thickenss in um
w1 = 20. # foil plasma energy in eV
w0 = 0.7 # air (gap) plasma energy in eV
gth = 2.5*d1*w1 # gamma threshold

alp = 1./137.

print ("gth = ", gth)

ge = 2.e3 # electron gamma

thmax = 10. # max angle in mrad
dth0 = 1.e-2 # theta bin width in mrad
th0 = np.arange(0, thmax, dth0) # angle in mrad

th = th0*1.e-3 # mrad to rad
dth = dth0*1.e-3 # mrad to rad
nth = th.shape[0]
print ("nth = ", nth)

ww = 1.e4 # energy in eV == 10 keV

cs0 = w0/ww
cs1 = w1/ww

a0 = cs0*cs0 + np.power(1./ge, 2.)
```

```
a1 = cs1*cs1 + np.power(1./ge, 2.)

b0 = np.power(th, 2.) + a0
b1 = np.power(th, 2.) + a1

# TR single surface emission
ss = dth*2.*alp/np.pi*np.power(th, 3.)*np.power(1./b0 - 1./b1, 2.)/ww # dN/dw

ph1 = 0.5*ww*d1*(np.power(th, 2.) + a1)

# TR single foil emission
sf = 4.*ss*np.power(np.sin(0.5*ph1), 2.)

maxsf = np.max(sf)
print ("maxsf = ", maxsf)

sf1 = sf/maxsf

dist0 = 1000. # rad-detector distance in mm

# Mimosa chip pixel
nx = 576
ny = 576 # 1172, just half and to have square shape

pitch = 18.5e-3 # pitch in mm, i.e. 18.5 um

x0 = -nx/2.*pitch
y0 = -ny/2.*pitch

x = x0 + np.arange(0, nx, 1)*pitch
y = y0 + np.arange(0, ny, 1)*pitch

xypix = np.zeros((nx, ny))
xyth = np.zeros(nth)

nevt = 2000000
good = 0
for i in range(nevt):
  _it = np.random.randint(nth)
  _th = th[_it]
  _sf = sf1[_it]
  _rr = np.random.random()
  if(_sf < _rr):
    continue

  xyth[_it] += 1.
```

```
  _phi = 2.*np.pi*np.random.random()

  _x = dist0*np.sin( _th )*np.cos( _phi )
  _y = dist0*np.sin( _th )*np.sin( _phi )

  # particles within +/- 2 pixels
  if( _x > - 2.*pitch and _x < 2.*pitch and _y > -2.*pitch and _y < 2.*pitch):
    continue

  _ix = int(( _x - x0)/pitch)
  _iy = int(( _y - y0)/pitch)

  if(_ix<0 or _ix >= nx or _iy<0 or _iy>=ny):
      continue

  xypix[_ix][_iy] += 1.
  good += 1

for i in range(nx):
    for j in range(ny):
        if (xypix[i][j] < 1.):
            xypix[i][j] = np.nan

print ("good = ", good)
print ("Rejection efficiency =",np.sum(xyth)/float(nevt) )

fig,ax = plt.subplots(1)
ax.plot(th0, sf1)
#ax.set_yscale("log")
ax.set_ylim(1.e-4,1.1)
ax.set_xlabel(r"$\theta$ (mrad)")
ax.set_ylabel(r"dN/d$\theta$ (AU)")
ax.grid(True)

fig1,ax1 = plt.subplots(1)
ax1.plot(th0, xyth)
ax1.set_xlabel(r"$\theta$ (mrad)")
ax1.set_ylabel(r"Number of Events")
ax1.grid(True)

lmin2 = np.nanmin(xypix)
print ("lmin2 = ", lmin2)
lmax2 = np.nanmax(xypix)
print ("lmax2 = ", lmax2)
lmin2 = 5
```

```
lmax2 = 20
levels2 = np.linspace(lmin2, lmax2, 100)
norm2=colors.Normalize(vmin=lmin2, vmax=lmax2)
ticks = np.linspace(lmin2, lmax2, 4)
xm, ym = np.meshgrid(x, y)
fig2,ax2 = plt.subplots(1)
cs2 = ax2.pcolormesh(xm, ym, xypix, cmap=cm.jet, norm=norm2)
cb2 = fig2.colorbar(cs2, ax=ax2, cmap=cm.jet, norm=norm2, drawedges=False, extend='both')
cb2.set_label(r"Number of Events/pixel")
cb2.set_ticks(ticks, update_ticks=True)
ax2.set_xlim(-2., 2.)
ax2.set_ylim(-2., 2.)
ax2.set_xlabel(r"X $-$ X$_{part}$ (mm)")
ax2.set_ylabel(r"Y $-$ Y$_{part}$ (mm)")
ax2.grid(True)

plt.show()
```

References

[1] https://beamlineforschools.cern/sites/beamline-for-schools.web.cern.ch/files/BeamAndDetectors_2021.pdf.

[2] V. L. Ginzburg. Radiation by uniformly moving sources (Vavilov-Cherenkov effect, transition radiation, and other phenomena). *Phys. Usp.*, 39:973–982, 1996.

[3] J. Alozy et al. Identification of particles with Lorentz factor up to 10^4 with Transition Radiation Detectors based on micro-strip silicon detectors. *Nucl. Instrum. Meth. A*, 927:1–13, 2019.

[4] J. Alozy et al. Studies of the spectral and angular distributions of transition radiation using a silicon pixel sensor on a Timepix3 chip. *Nucl. Instrum. Meth. A*, 961:163681, 2020.

[5] P. A. Zyla et al. Review of Particle Physics. *PTEP*, 2020(8):083C01, 2020.

[6] https://web-docs.gsi.de/~stoe_exp/web_programs/x_ray_absorption/index.php.

[7] https://telescopes.desy.de/Hardware#Telescope_infrastructure.

[8] J. Baudot, G. Bertolone, A. Brogna, G. Claus, C. Colledani, Y. Degerli, R. De Masi, A. Dorokhov, G. Dozière, W. Dulinski, M. Gelin, M. Goffe, A. Himmi, F. Guilloux, C. Hu-Guo, K. Jaaskelainen, M. Koziel, F. Morel, F. Orsini, M. Specht, I. Valin, G. Voutsinas, and M. Winter. First test results of mimosa-26, a fast cmos sensor with integrated zero suppression

and digitized output. In *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, pages 1169–1173, 2009.