This simple exercise is thought to collect very basic information regarding radioactive sources and cosmic rays, the energy loss and signal creation in silicon by different types of radiation, and deduce which tests of silicon detectors can be performed in a lab (without dedicated test beams).
Everybody is invited to contribute to do the exercise and insert the missing information.
For any question, please ask me (Silvia, s.masciocchi@gsi.de) or write simply in between lines.

I suggest that people add information and text using different colors, so that we can follow up the inputs, questions, discussion (pick your prefered color!). Priority is given to Felicitas, Maurice and David!
Silvia - I remain black for simplicity
Bogdan
Pascal
Maurice
David
Felicitas
Kai

I gave twice the course on "The physics of particle detectors". You can consult the slides of the course at https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/

Section 1: interaction of radiation with matter

Let's collect some very basic information and distributions:

- **Charged particles** traversing our detectors will lose energy primarily via the process of ionization. The energy loss per unit path length in the material (possibly

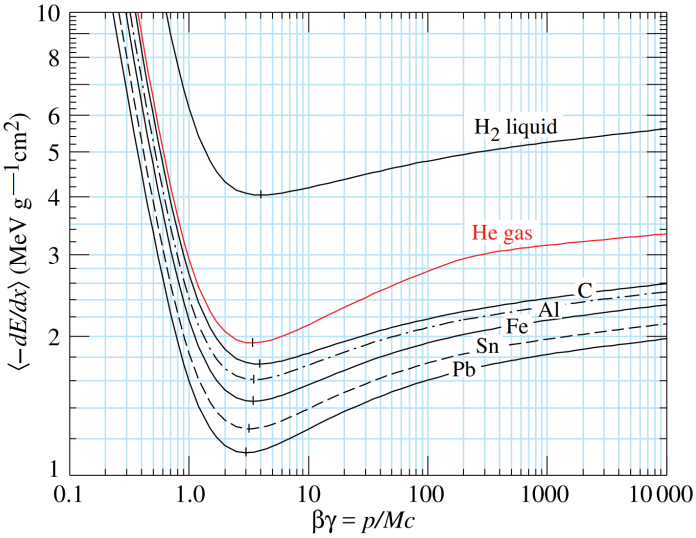
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 4\pi N_{\mathrm{A}} r_e^2 m_e c^2 z^2 \frac{Z}{A}\,\frac{1}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right)$$

divided by the density of the material itself) is described by the Bethe-Bloch formula:
One can find this expression for example in the book "particle detectors" from Grupen and Shwartz.
Hereby is $-\, dE/dx$ the energy loss E per distance ds thru a material with the density ρ and the correlation $dx = ds\, *$ ρ, N_A the Avogadro Number, r_e the classical electron radius, m_e the electron mass, c the speed of light, z the charge of the incident particles, Z and A the atomic numbers, □ the velocity of the particle divided by c, γ the Lorentz factor, I the mean excitation energy and δ (depending on □) the factor of the relativistic extension of the transverse electric field of the particle.
This formula is only valid for charged particles, and it only describes the energy loss by ionization. In the specific case of electrons, it needs some modification. Quoting the review from the PDG (particle data group): "Stopping power differs somewhat for

electrons and positrons, and both differ from stopping power for heavy particles because of the kinematics, spin, charge, and the identity of the incident electron with the electrons that it ionizes". This identity makes it necessary to consider quantum corrections. A modified Bethe-Bloch formula describes the energy loss of electrons and positrons by ionization. It should be remembered that electrons with energy above a certain threshold (the so-called critical energy) primarily lose energy via a different process, which is the one of Bremsstrahlung. In Bremsstrahlung, the energy loss is achieved by interaction with a nucleus, whereby photons are emitted by the electron. Above the critical energy, Bremsstrahlung is dominant. Below, ionization is dominant.

Please also add what the symbols represent :). Also, is this valid for all particles or?

What are these orange questions referred to?



[Fig. 33.2 from 33. Passage of Particles Through Matter]

[please link or insert the plot showing this distribution as a function of the particle energy ($\beta\gamma$), contained in the particle data book available at http://pdg.lbl.gov/]

This plot shows the energy loss per distance in different mediums (divided by the material density).

Highlight the features of this distribution which are relevant for us:

Region 1:

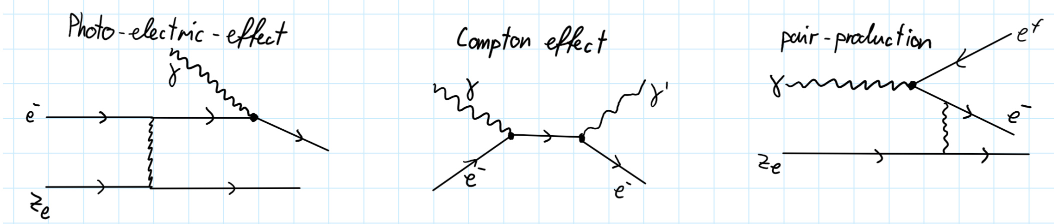
Important aspects of this diagram are firstly the steep increase for low values of $\beta\gamma$ ($-dE/dx \sim 1/\beta^2$). We can see this in the formula, whereby for small β in the bracket the logarithmic term becomes nearly 1, the β^2 crosses out with the $1/\beta^2$ and the last term is zero.This causes that the $1/\beta^2$ out of the bracket becomes dominant for the logarithmic part of the bracket and the rest stays constant. Physically one can explain this phenomena with the increasing interaction time of the particles with the absorber materials for low β.

Region 2:

Furthermore we can identify a minimum which is located around 2 to 3 βγ for all shown materials (normalised to the density).
[Here I removed the comment on minimizing the energy loss, which is wrong. Maurice, if you have doubts or questions about this, please let me know.]

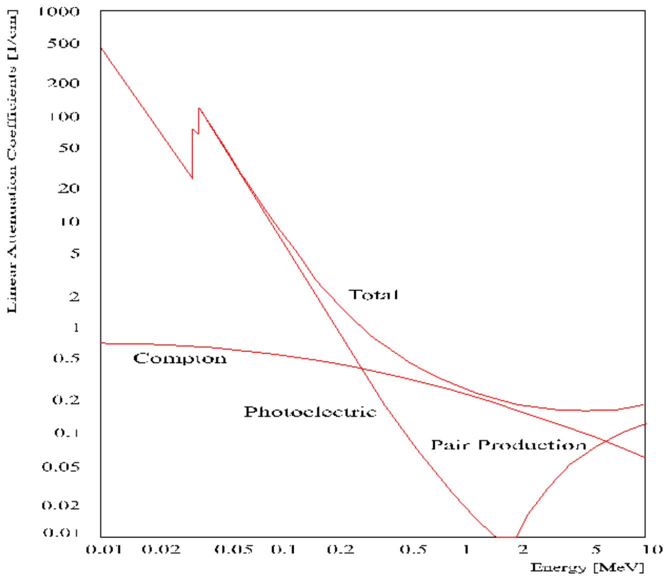
Region 3:
After the minimum one can see an increase of the energy loss, due to e-h-pair-production, bremsstrahlung, and photonuclear interactions. Increasing relativistic effects damp the mentioned effects, by polarizing the traversing medium, due to an extended transverse electric field of the incident particle.
At the relativistic rise ($\sim \ln \gamma^2$), relativistic effects on the transverse electric field increase the stopping power
This holds for all charged particles, namely alpha particles and electrons/positrons from radioactive sources, and for muons (or other charged particles) in cosmic rays.

- **Photons** interact with material via the following processes:
  - photoelectric effect, important for low energies up to around one Mev where the other effects take over. The photon becomes *completely absorbed by an electron* (the sentence is not quite correct: an electron, particularly a free electron, cannot "absorb" a photon. What happens is that the entire energy of the photon is used to liberate one electron from one of the atomic shells) Yes, that's why you can see absorption maxima and minima in this region of the plot. They reflect the target materials shell structure.
  - Compton effect, important for energies around 100 keV to a few MeV. The photon scatters elastically with an electron, meaning that it will not be absorbed completely. Note that the photon frequency changes! Why? … $E = \hbar\omega$ But due to the fact that it transfers some energy to the electron the photon will have less energy after the process and therefore a lower frequency.
  - Pair production, important for "high" energies. Needs at least the energy corresponding to the mass of two electrons (1.022 MeV), so the photon can convert its energy to an electron-positron pair, by interacting with an atomic nucleus
  - Can you think of Feynman diagrams for all of these processes.



[comment on the relative importance of the process wrt to the photon energy]
  - the absorption coefficient depends on the photon energy. For low energies the photoelectric effect is dominant, while for rising energies, the compton effect

becomes more and more apparent, and for high energies above ~1 MeV pair production occurs, which dominates for energies above ~10^7 eV:

- What defines the threshold for the pair production to kick in?
- In principle it’s possible to create an electron-positron pair, when the photon energy is at least equal to the rest masses of the two particles, i.e. $2 \cdot 0.511$ keV
- 

Section 2: Natural sources of radiation

2.1 Particle energy

What we can use in a lab are radioactive sources (alpha, beta, gamma sources) or cosmic rays.
Typical sources are listed below. Bogdan, could you please cross check what is available at GSI and in Heidelberg (if possible)? For HD we already have a list; this week we will compute the one for GSI as well :) For each element, let’s collect the typical energy (range) of the emitted radiation:

- Alpha:
    - Americium-241. (Wikipedia) The α-decay energies are 5.486 MeV for 85% of the time (the one which is widely accepted for standard α-decay energy), 5.443 MeV for 13% of the time, and 5.388 MeV for the remaining 2%

- Beta:
    - Strontium-90: (Wikipedia) ^{90}Sr undergoes β^- decay with a half-life of 28.79 years and a decay energy of 0.546 MeV distributed to an electron, an anti-neutrino, and the yttrium isotope **^{90}Y**, which in turn undergoes β^- decay with half-life of 64 hours and decay energy 2.28 MeV distributed to an electron, an anti-neutrino, and ^{90}Zr (zirconium), which is stable. ^{90}Sr undergoes β^- decay with a half-life of 28.79 years and a decay energy of 0.546 MeV distributed to an electron, an anti-neutrino, and the yttrium isotope **^{90}Y**, which in turn undergoes β^- decay with half-life of 64 hours and decay

energy 2.28 MeV distributed to an electron, an anti-neutrino, and ^{90}Zr (zirconium), which is stable.

- Gamma:
  - Cobalt-60: … (Information source: Wikipedia) Cobalt-60 undergoes β^- decay with a half life of 5.272 years. It decays in three branches into three different excited states of Nickel. The first branch decays with a probability of 99.88% and the decay energy of 0.31 MeV into the excited state with an energy of 2.5 MeV (referenced to the ground state of Nickel). The second branch decays with a probability of 0.0022% and the maximum decay energy of 0.665 MeV into the excited state with an energy 2.16 MeV and the third branch decays with the probability of 0.12% and the maximum decay energy of 1.48 MeV into the excited state with an energy 1.33 MeV. The decay energy is distributed to an electron and an antineutrino. The excited states of nickel decay into the ground state, by emitting a photon. They can either fall into the ground state or in another excited state with a lower energy as the current state. For this reason six different photon energies can occur: The two dominant decays are the transition from the 2.5 MeV state to the 1.33 MeV state with the energy of the emitted photon of 1.17 MeV and the 1.33 MeV state into the ground state with a photon energy of 1.33 MeV.(add information in a similar way, to get some information on the energy of the resulting photons)

For cosmic rays, we can simplify the description, assuming that they are mostly muons in the energy range …. from 10 to 100 GeV (source: 24. COSMIC RAYS)

2.2 Energy loss and particle range (until stopping) in matter

- Below is a Table with some particle ranges calculated from the Bethe Bloch formula as above. (Note that density and Shell corrections have been neglected)
- One can calculate the particle range, by integrating the inverse of this Formula all the way up until the particle energy E_0
- The mean Excitation Potential (MEP) Ihas been derived empirically (See William R. Leo - Techniques for Nuclear and Particle Physics Experiments)

	MEP (I)	α- Particle, z = 2 m = 3727 MeV/c^2	β- Particle, z = 1, m = 0.511 MeV/c^2			
Energy		5 MeV	0.5 MeV	5 MeV	50 MeV	5000 MeV
N (Z=7, A=14)	91 eV	1 cm	295 cm	250 m	434 m	24.3 km
Al (Z=13, A=27)	163 eV	3.8 um	0.12 cm	6.50 cm	92.2 cm	12.4 m
Si (Z=14, A=28)	172 eV	4.2 um	0.13 cm	6.99 cm	226.0 cm	11.3 m

Pb (Z=82, A=207)	826 eV	0.9 um	0.03 cm	0.92 cm	15.7 cm	4.3 m

-

2.3 Particle rate

In addition to the information about the energy range of the particles, we need an estimate of the particle rate (number of particles per cm2 x second), for the different cases.

For cosmic rays we need to assume a realistic rate of 100 particles per (m^2 * s * sr), whereby sr is the square radian. (source: 24. COSMIC RAYS)

For radioactive sources, we need an estimate of their activity …. The activity varies, but for many sources, for example Cobalt-60 or Caesium-134 it ranges in the order of a few 10 TBq/g, whereby Bq equals to the number of disintegrations per second (source: BMU Strahlenschutz, similar results on Wiki). So one can estimate the activity to $10^{13}\ Bq/g$.

Radionuklid	Halbwertszeit[#] t_r in s	Auf die Masse bezogene Aktivität $a_{m,r}$ in $Bq \cdot g^{-1}$
P-32	$1,23 \cdot 10^{6}$	$1,06 \cdot 10^{16}$
Cr-51	$2,39 \cdot 10^{6}$	$3,42 \cdot 10^{15}$
Mn-54	$2,70 \cdot 10^{7}$	$2,86 \cdot 10^{14}$
Co-58	$6,12 \cdot 10^{6}$	$1,18 \cdot 10^{15}$
Co-60	$1,66 \cdot 10^{8}$	$4,18 \cdot 10^{13}$
Fe-55	$8,68 \cdot 10^{7}$	$8,74 \cdot 10^{13}$
Fe-59	$3,85 \cdot 10^{6}$	$1,84 \cdot 10^{15}$
Ni-63	$3,16 \cdot 10^{9}$	$2,10 \cdot 10^{12}$
Zn-65	$2,11 \cdot 10^{-7}$	$3,04 \cdot 10^{14}$
Sr-90	$9,08 \cdot 10^{8}$	$5,11 \cdot 10^{12}$
Tc-99^{m}	$2,18 \cdot 10^{4}$	$1,93 \cdot 10^{17}$
I-125	$5,13 \cdot 10^{6}$	$6,51 \cdot 10^{14}$
I-131	$6,93 \cdot 10^{5}$	$4,60 \cdot 10^{15}$
Cs-134	$6,52 \cdot 10^{7}$	$4,78 \cdot 10^{13}$
Cs-137	$9,52 \cdot 10^{8}$	$3,20 \cdot 10^{12}$
Tl-201	$2,63 \cdot 10^{5}$	$7,90 \cdot 10^{15}$
Pu-238	$2,77 \cdot 10^{9}$	$6,34 \cdot 10^{11}$
Pu-239	$7,61 \cdot 10^{11}$	$2,30 \cdot 10^{9}$
Pu-240	$2,07 \cdot 10^{11}$	$8,40 \cdot 10^{9}$
Pu-241	$4,53 \cdot 10^{8}$	$3,82 \cdot 10^{12}$
Am-241	$1,36 \cdot 10^{10}$	$1,27 \cdot 10^{11}$
Cm-242	$1,41 \cdot 10^{7}$	$1,22 \cdot 10^{14}$
Cm-244	$5,71 \cdot 10^{8}$	$3,00 \cdot 10^{12}$

In reality, the activity is lower …. Compute particle rate …

To calculate the particle rate, we need to make some assumptions on the mass of the source and the distance to our target/ the place where we want to know the particle rate. To simplify things, let's assume we have a source of 1 g mass, it has a distance of 10 cm to the target of 1 cm^2 and as well the activity of $10^{13}\ Bq/g$ we estimated above. Therefore the squareradian would be $1cm^2/(10cm)^2$ which equals to 0.01. In this case, the particle rate would be $10^{11}/(cm^2 * s * sr)$. If the source is 1 m away, we get a rate of $10^{9}/(cm^2 * s * sr)$. This shows that the rate is depending extremely on the experimental setup.

This rate will be important later (below) to estimate whether we can take data without a trigger or we need one (see later, section 6).

Section 3. Signal produced in the MAPS chip

Using the information collected so far, we calculate how much charge is produced in an ALPIDE chip (50 micrometer thick layer of silicon) by a traversing particle (alpha, electron or positron, muon, photon) having the energies listed under section 2.
Use the formula for dE/dx (use again the particle data book for reference), the density of silicon, the thickness given.

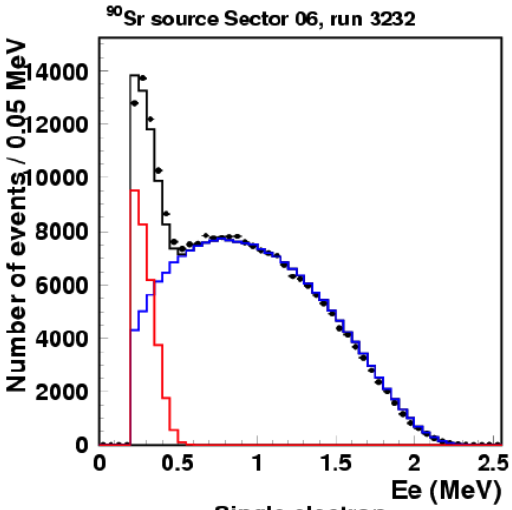
Example: when traversing 50 micron of silicon, an alpha particle of 5.486 MeV loses … 6.93 MeV. Because it loses more energy than it has kinetic energy, the particle would not get through the whole 50 micrometer. Therefore, it produces …. up to $1.93 * 10^{6}$ electron-hole pairs.
An alpha particle with 5.443 MeV loses 6.96 MeV, which would produce also up to around $1.93 * 10^{6}$ electron-hole-pairs.
An alpha particle with 5.388 MeV loses 7.01 MeV, which would produce also up to around $1.95 * 10^{6}$ electron-hole-pairs.
If the alpha particle does not decay further, the kinetic energy is the maximum energy, the alpha particle can deposit in the material. Therefore only $1.52 * 10^{6}$ electron-hole-pairs could be produced for all three decay modes.

Now we take a look on β-decay:
The critical energy of silicon is for both electrons and positrons around 40 MeV. For this reason, electrons with a low energy of a few MeV or less interact mostly by collisions and is therefore describable by the Bethe-Bloch-formula. So for Strontium-90, which undergoes β -decay with an energy of 0.546 MeV distributed to an electron, a anti-electron-neutrino and the Yttrium-90 isotope. Since we can not detect a neutrino on such short scales, due to the fact that neutrinos rarely interact with matter, we only will see the decay products of Yttrium-90 (delayed, on account to the half-life of 64 hours) and the electron.
In Tab.3.1 the energy loss and the produced e-h-pairs are shown:

Initial Energy [MeV]	0.546	2.28
Total Energy loss [MeV]	0.021	0.020
# e-h-pairs	5800	5500

Tab.3.1 Energy-loss of electrons from the Sr-90 decay

Since the decay-product zirconium-90 is stable, there are no other particles expected.
Consider the effective distribution of the electron energy, in the typical spectrum from beta decay(s)



Single electron

Nextly we take a look on the decay of Cobalt-60:

Firstly Cobalt decays also by β^--decay into three excited states of Nickel shown in Tab.3.2

Initial Energy [MeV]	0.31	0.665	1.48
Probability of associated decay-branch [%]	99.88	0.0022	0.12
Total Energy loss [MeV]	0.025	0.020	0.019
# e-h-pairs can be produced	6800	5600	5300

Tab.3.2 Energy-loss of electrons from the Co-60 decay

Because of the domination of the first decay branch and the continuous energy distribution of the electron, it will be very difficult to distinguish between these three decay modes.

The excited states of Nickel decay further by emitting photons. The maximum energy of a photon is 2.5 MeV, whereby the highest excited state decays to the ground state. The two dominant processes are the decay from the highest excited state with 2.5 MeV to the lowest with 1.33 MeV and from the lowest excited state with 1.33 MeV to the ground state.
Photons in this energy scale mostly lose their energy due to the photoelectric effect or Compton scattering. Either they lose their complete energy to one electron (mostly for energies below 1 MeV), or they scatter by the Compton effect and lose a significant part of its energy to the electron. Mostly the electrons get in an excited state, but do not ionize so much. Therefore there will be rarely enough e-h-pairs produced to create a signal.

Last but not least we have cosmic rays, which we assume to be mostly muons. Since the energy ranges from 10 to 100 GeV, we will calculate the energy loss for 10, 50 and 100 GeV.

Initial Energy [GeV]	10	50	100

Total Energy loss [MeV]	0.0256	0.0286	0.0299
# e-h-pairs can be produced	7100	7900	8250

Tab.3.3 Energy-loss of cosmic muons

And so on for all cases.
There will be one radiation type which most often does not leave enough energy to create a signal.
To calibrate and cross check your calculation so far, calculate also how many e-h pairs are produced by a MIP in 300 micron of silicon. Look for this number in literature and compare! Please add the number here, and some reference which you will find :-)
As a crosscheck we will calculate now how many e-h-pairs are produced in 300 micron of silicon from a MIP-muon. A muon is minimal ionizing at 273 MeV. At Muons in silicon (Si) the literature value for such a muon is given as 1.664 MeV cm²/g. If we insert the density of silicon and the range of 300 µm, as a result we get an energy loss of 116.3 keV which corresponds to 32127 e-h-pairs. If i use my calculation method (python script will be inserted below), we get 116.4 keV and 32153 e-h-pairs. As one can see, the error is less than 0.1%.

4. Total energy loss by the incoming radiation per layer

Every chip might have some protection material around it (a thin foil for protection? A solid, thin box?)
Pascal and Bogdan can give an estimate of the materials used, and the thickness of the protection layer.
The two REF arms and the DUT have enclosures with beam entrance and exit windows made of tin foil and kapton tape, which act as shields from light. The alu foils, the kapton, the chips themselves and the air between them have to be taken into account. For kapton, take 50 um (2-mil type; no idea what they used, but it's the most common), for alu take 16 um (household foil), then approx 2 cm of air between each plane. The silicon in the chip has 50 um. Metal/transmission lines on the chip, CMOS parts and other components on the active matrix part of the chip can be neglected.
So, from the beam side you would have something like: kapton+alu+2cm air+first Si plane+ 2cm air + second Si plane + …

Particles will lose energy also traversing those. Compute that too.
First the energy loss in 50 µm Kapton:
The alpha particles of Americium will lose their complete energy in the kapton film and will be stuck there. For this reason , we won't calculate the alpha energy loss for other materials.

Element (Particle)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics (µ)	Cos. (µ)	Cos. (µ)
Initial Energy [MeV]	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000

Total Energy loss [keV]	14.4	13.7	17.0	13.9	13.4	19.7	23.3	24.8

Tab.4.1 Energy loss through 50 µm Kapron

Now the energy loss in 16 µm Aluminium foil, excluded alpha particles as mentioned earlier:

Element (Particle)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics (µ)	Cos. (µ)	Cos. (µ)
Initial Energy [MeV]	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000
Total Energy loss [keV]	11.2	10.8	13.1	10.9	10.5	15.8	18.8	20.1

Tab.4.2 Energy loss through 16 µm Aluminium

As one can see, Aluminium has a comparable stopping power to Kapton, but is still slightly lower.

Furthermore the energy loss in 2 cm Air:

Element (Particle)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics (µ)	Cos. (µ)	Cos. (µ)
Initial Energy [MeV]	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000
Total Energy loss [keV]	4.73	4.5	5.57	4.57	4.39	6.47	7.65	8.16

Tab.4.3 Energy loss through 2 cm Air

The energy loss in air is significantly smaller, compared to Aluminium and Kapton.

Last but not least the energy loss of a 5 mm thick scintillator (source:PLASTIC SCINTILLATOR (VINYLTOLUENE BASED) is shown:

Element (Particle)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics (µ)	Cos. (µ)	Cos. (µ)
Initial Energy [MeV]	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000
Total Energy loss [MeV]*	0.456 (1.04)	0.99	0.31 (1.23)	0.665 (1.01)	0.97	1.41	1.66	1.77

Tab.4.4 Energy loss through 5 mm Scintillator

*: in brackets the calculated energy loss, which is not realistic, because the particle can not lose more energy than its kinetic energy. The particle wont penetrate the material

The energy loss in the scintillator is the highest of all materials due to the thickness.

In some setup we will need a trigger (when the rate of incoming particles is too low, using a random trigger for the readout might mean to have too few signals over a reasonable time, or to need months to collect enough statistics). A typical solution is provided by a pair of scintillators: one in front of all chips, one behind all chips. If both scintillators see a passing particle in “coincidence” (with the due delay compensation in the logic circuit), this can provide a trigger to read out the chip(s) in between. Take a thickness of 5-10 mm of a typical plastic scintillator and calculate also the energy loss of each particle type in there.

Estimating the total energy loss is very important: high energy particles (the cosmic muons) will lose only a small fraction of their total energy crossing one ALPIDE chip and its mounting “box” and even the scintillators. But how about the electrons and even more the alphas? Compute the total energy loss and what fraction of the initial energy of the particle that is.
Following the total energy loss of the above discussed particles are shown:

Element (Particle)	Ameri. (alpha)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics μ	Cos. μ	Cos. μ
Initial Energy [MeV]	5.443	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000
Total Energy loss [MeV]*	5.443 (423)	0.456 (4.5)	2.28 (4.7)	0.31 (4.6)	0.665 (4.5)	1.48 (4.6)	5.68	6.23	6.47
Fraction [%]	100	100	100	100	100	100	0.05	0.01	0.006

Tab.4.5: Total energy loss through the ALPIDE Telescope
*: in brackets the calculated energy loss, which is not realistic, because the particle can not lose more energy than its kinetic energy. The particle wont penetrate the whole telescope.

As we see, only the muons traverse the whole telescope
Perfect conclusion. After solving also the point 2.3, we will be able to conclude that we do not need to despair at this point, in fact:

- We better do not use much an alpha source, since the alpha particles will get stuck in the first layer crossed. Maybe one could consider to illuminate an ALPIDE directly, to see whether one gets indeed a super-high signal (for curiosity)
- When we will be using a beta source, the rate (see point 2.3) should be high enough that measurements can be done in the lab without the need of an external trigger (therefore no scintillators and the electrons can ge through something)
- When we work with cosmics, they lose a negligible amount of energy passing whatever layer of material, so we can easily use also two nice scintillators to trigger. In that case, a trigger is mandatory, otherwise we will need months to take some measurement.

So life is good and plans look really promising (corona virus excluded …).

5. Number of planes traversed

With the information from section 4, for every radiation type considered, calculate how many layers can be crossed (from 1 to 7), before the particle might be stopped (having lost all its energy).
Consider the case with and without one scintillator in front of all planes.

With scintillator:

Element (Particle)	Ameri. (alpha)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics μ	Cos. μ	Cos. μ
Initial Energy [MeV]	5.443	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000
Layer in which particle stops (#detector layers,1 to 7)	First scinti (0)	First scinti (0)	Last scinti (7)	First scinti (0)	First scinti (0)	Last Kapton (7)	Not stopped (7)	Not stopped (7)	Not stopped (7)

Tab.5.1: Number of traversed planes through the ALPIDE Telescope with scintillators

Without Scintillator:

Element (Particle)	Ameri. (alpha)	Stront. (e)	Stront. (e)	Cobalt (e)	Cobalt (e)	Cobalt (e)	Cosmics μ	Cos. μ	Cos. μ
Initial Energy [MeV]	5.443	0.546	2.28	0.31	0.665	1.48	10 000	50 000	100 000

Layer in which particle stops (#detector layers,1 to 7)	First Kapton (0)	Not Stopped (7)	Not Stopped (7)	5. Det. (5)	Not stopped (7)	Not stopped (7)	Not stopped (7)	Not stopped (7)	Not stopped (7)

Tab.5.2: Number of traversed planes through the ALPIDE Telescope without scintillators

One can remark that for the electrons only the ones with relatively high energy can pass first the scintillator. FUrthermore it can be mentioned that without scintillators all electrons but for one specific energy will pass the whole telescope. And this one electron decay mode from the low energy cobalt decay will most probably stuck in the fifth detector layer and so also traverse the DUT.

6. Think of small setups for the lab

Now it is time to put together ALL information, and think about which setups we could build to do some interesting measurements in the lab. We could imagine to have 2, 3 or 4 planes with one ALPIDE chip each, put parallel to each other in a stack.

We can use a **radioactive source**: which one at best? Americium is a bad source, since the emitted alpha particles cant penetrate a single layer. Sr-90 has a low activity compared to Cobalt, so we would need a coincidence measurement with scintillators for it. Unfortunately only one decay mode would provide enough energy, so the electrons could penetrate the scintillator (for both Sr-90 and Co-60). In case we want to see how the chip behaves on different energy regimes (even if the electron energy is distributed, it would be nice to see more than one peak), we should take the Cobalt source, since it has a higher activity and so we don't need a scintillator for coincidence anymore. In this case all three decay modes could provide electrons, which could penetrate up to 5 detector layers.
If this variety is not important, Sr-90 is also a good source to test a coincidence measurement. Cosmic rays have a significantly lower rate and therefore they would be hard to detect. But if we have no other sources around, cosmics should be the only source of particles which can penetrate the whole detector. Due to the wide energy spectrum it could be interesting to see the results of the measurement too.
But all in all Cobalt-60 is probably the best source.
(such that the particles would cross all planes). Do we need a trigger from scintillators, or is the rate high enough to work without trigger? Will the particle make it, through 2 scintillators and n planes of silicon?

If we use simply **cosmic rays**, their energy is much higher and will be enough to cross 2 scintillators, n planes of silicon and more. But what is the rate? Do we need a trigger?

As soon as we reach this point with reasonable numbers, we can discuss about the best small setup to build together in the lab :-)
That will be lots of fun!

Python Code:

Calculate range of Particles with Bethe-Bloch:

```
# Script to calculate the range of a charged particle in an absorber medium
# NOTE: Density and Shell corrections have been neglected!!! This
# Program will only yield accurate values for energies between 1MeV and 1000MeV
import numpy as np
import matplotlib.pyplot as plt
import scipy.integrate as scp

#Global Variables
C_BB = 0.307          #Bethe Bloch Formula constant MeV cm2/g
m_e = 9.109*10**(-28)   #g
c = 3*10**10          #cm/s

############## ENTER PARTICLE AND ABSORBER INFORMATION HERE ##################
#Particle Variables
name_particle = 'Electron'
z = 1       # Particle Charge
m_0 = 0.511 # Particle Mass in MeV/c2
p_0 = 0.546  # Particle Momentum in MeV/c

#Absorber Variables
name_absorber = 'Silicon'
Z = 14
A = 28
rho = 2.33         #g/cm3
##############################################################################

#Functions
def I(Z):
    if (Z<13):
        return Z*(12+7/Z)*10**(-6)
    else:
        return Z*(9.76+58.8*Z**(-1.19))*10**(-6)
def BB(beta,gamma):
    return C_BB*rho*z**2*Z/(A*beta**2)*(np.log(2*m_e*c**2*gamma**2*beta**2/I(Z))-beta**2)
def calc_gamma(p_0):
    return 1+p_0/m_0
def calc_beta(gamma):
    return np.sqrt(1-1/gamma**2)

def calc_range():
    bins = 10000 #choose, over how many bins should be integrated (~10.000)
    xaxis = np.linspace(0.1,p_0,bins)
    gamma = calc_gamma(xaxis)
    beta = calc_beta(gamma)

    # "integrate" range
    bin_width = xaxis[1]-xaxis[0]
    dx = 0
    for i in range(bins):
        dx += bin_width/BB(beta[i],gamma[i])
```

```
    print('gamma_0 = ', gamma[bins-1])
    print('beta_0 = ', beta[bins-1])
    print('Stopping Power at maximum energy: ',
          round(BB(beta[bins-1], gamma[bins-1]),2),
          'MeV per cm')
    if abs(dx) >= 0.01:
        print("Range of an {} with energy {} MeV in {}: {}cm".format(name_particle, p_0, name_absorber, round(abs(dx),4)))
    if abs(dx) < 0.01:
        print("Range of an {} with energy {} MeV in {}: {} microns".format(name_particle, p_0, name_absorber,
round(abs(dx*10**4),4)))

    # Plot bethe-bloch (optional)
    #plt.figure()
    #plt.xlabel('Particle Energy [MeV]')
    #plt.ylabel('Stopping power -dE/dx [MeV/cm]')
    #plt.plot(xaxis,BB(beta, gamma))
    #plt.axvline(p_0, linewidth=0.5, color='black') #Draw a line atMaximum energy
    #plt.show()

#Calculate
calc_range()
```

Code to section 3 and 4:

```
# load standard libraries
import numpy as np   # standard numerics library
import matplotlib.pyplot as plt   # for making plots

# properties of silicon
A_Si  = 28.09e-3 #kg/mol
Z_Si  = 14
I_Si  = 173 #eV
rho_Si= 2.329e3 #kg/m^3
x_0_Si= 0.2015
x_1_Si= 2.8716
C_Si  = 4.4355
a_Si  = 0.14921
k_Si  =3.2546
rad_length_Si =9.370e-2 #in m

#Energy loss:
def Bethe(E,E_0,n,d_x,Z=Z_Si,A=A_Si,I=I_Si,rho=rho_Si,x0=x_0_Si,x1=x_1_Si,C=C_Si, a=a_Si, k= k_Si):
    N_A = 6.022e23  #1/mol
    e   = 1.602e-19 #C
    c   = 2.998e8   #m/s
    r_e = 2.818e-15 #m
    m_e = 9.109e-31 #kg
    E_e = 511e3        #eV
    z   = n                                  #from incident particle, Z,A are from the absorber
    K   = 4*np.pi*N_A*r_e**2*E_e     #eV*m^2/mol constant: 0.3 MeV *cm^2/mol
    gamm= ((E_0+E)/E_0)
    pc  = np.sqrt(2*E_0*E+E**2)
    beta= pc/(E+E_0)
    x   = np.log10(beta*gamm)


    if x>= x1:
        delt=2*np.log(10)*x-C
        print(1)
    elif (x < x1) and (x>=x0):
        delt=2*np.log(10)*x-C+a*(x1-x)**k
        print(2)
```

```
    else:
        delt=0
        print(3)



    d_E  = rho* d_x* K* z**2 * Z/ A/ beta**2 *(np.log(2* E_e* gamm**2 *beta**2 /I )-beta**2 -delt /2)#eV
    d_E  = d_E*1e-6                         #unit:MeV
    print("Energy in MeV: "+str(d_E))
    return d_E



#electron hole pair production
def eh(E):
    N= np.round(E/(3.62e-6))
    print("maximum number of e-h pairs: "+str(N))
    #return N


#electron interaction with silicon
def electron(E,dx,X0=rad_length_Si ):
    dE= E*np.exp(-dx/X0)
    print((E-dE)*1e-6)

#properties of incident particles

#alpha:
m_alph  = 6.645e-27 #kg
n_alph  = 2
E_0_alph= 3727.4e6 #eV

#muon
E_0_mu= 105.7e6 #eV
m_mu= 1.884e-28
n_mu=1

#electron
E_0_e= 511e3 #eV
n_e=1


####test
Bethe(10e6,E_0_mu,n_mu,50e-6)


###################Section 4

#Bethe without delta, due to missing information:
#Energy loss:
def Bethe0(E,E_0,n,d_x,Z,A,I,rho):
    N_A = 6.022e23  #1/mol
    e   = 1.602e-19 #C
    c   = 2.998e8   #m/s
    r_e = 2.818e-15 #m
    m_e = 9.109e-31 #kg
    E_e = 511e3     #eV
    z   = n         #from incident particle, Z,A are from the absorber
    K   = 4*np.pi*N_A*r_e**2*E_e #eV*m^2/mol constant: 0.3 MeV *cm^2/mol
    gamm= ((E_0+E)/E_0)
    pc  = np.sqrt(2*E_0*E+E**2)
    beta= pc/(E+E_0)
```

```
    d_E  = rho* d_x* K* z**2 * Z/ A/ beta**2 *(np.log(2* E_e* gamm**2 *beta**2 /I )-beta**2)#eV
    d_E  = d_E*1e-6 #unit:MeV
    print("Energy in MeV: "+str(d_E))
    return d_E

# properties of kapton
Z_Ka  = 5.03
A_Ka  = 9.8e-3
I_Ka  = 79.6 #eV   #Information to kapton
rho_Ka= 1.42e3 #kg/m^3
rad_length_Ka =28.577e-2 #in m

# properties of Aluminium
Z_Al  = 13
A_Al  = 26.98e-3
I_Al  = 166 #eV
rho_Al= 3.97e3 #kg/m^3
rad_length_Al =7.04e-2 #in m

#properties of Air
Z_air = 0.49919
A_air = 1e-3
I_air = 85.7
rho_air=  1.205
rad_length_air = 3.039e2

#Energie loss through the whole telescope:
def tele(E,E_0,n):
    E_1 = Bethe0(E,E_0,n,5e-3,Z_Sci,A_Sci,I_Sci,rho_Sci)
    E_2 = Bethe0((E-E_1)*1e6,E_0,n,50e-6,Z_Ka,A_Ka,I_Ka,rho_Ka)
    E_g = E_2+E_1
    E_3 = Bethe0((E-E_g)*1e6,E_0,n,16e-6,Z_Al,A_Al,I_Al,rho_Al)
    E_g +=E_3
    E_4 = Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_4
    E_5 = Bethe((E-E_g)*1e6,E_0,n,50e-6)  #first plane
    E_g +=E_5
    E_6 = Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_6
    E_7 = Bethe((E-E_g)*1e6,E_0,n,50e-6)  #second plane
    E_g +=E_7
    E_8 = Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_8
    E_9 = Bethe((E-E_g)*1e6,E_0,n,50e-6)  #third plane
    E_g +=E_9
    E_10= Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_10
    E_11= Bethe((E-E_g)*1e6,E_0,n,50e-6)  #fourth plane DUT
    E_g +=E_11
    E_12= Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_12
    E_13= Bethe((E-E_g)*1e6,E_0,n,50e-6)  #fifth plane
    E_g +=E_13
    E_14= Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_14
    E_15= Bethe((E-E_g)*1e6,E_0,n,50e-6)  #sixth plane
    E_g +=E_15
    E_16= Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
    E_g +=E_16
    E_17= Bethe((E-E_g)*1e6,E_0,n,50e-6)  #seventh plane
    E_g +=E_17
```

```
E_18= Bethe0((E-E_g)*1e6,E_0,n,0.02,Z_air,A_air,I_air,rho_air)
E_g +=E_18
E_19= Bethe0((E-E_g)*1e6,E_0,n,16e-6,Z_Al,A_Al,I_Al,rho_Al)
E_g +=E_19
E_20= Bethe0((E-E_g)*1e6,E_0,n,50e-6,Z_Ka,A_Ka,I_Ka,rho_Ka)
E_g +=E_20
E_21= Bethe0((E-E_g)*1e6,E_0,n,5e-3,Z_Sci,A_Sci,I_Sci,rho_Sci)
E_g +=E_21
print("ENERGY OF THE DUT                : "+str(E_11))
print("TOTAL ENERGY                     : "+str(E_g))
```