Most of the things you might have wanted to know about detectors* (*But were afraid to ask)

Part 2

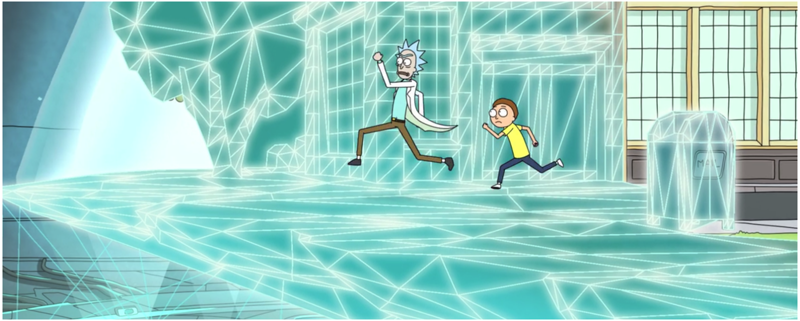
Simulations, because sometimes faking it is as good as the real thing (you wished)

Geoffrey Mullier

PIER, 23th September 2019

Detector simulations, why?

- We need to know if the design of a detector is viable
- We need to know be able to predict what the detector will see and modify the design accordingly
- Sometimes you do not have any hardware, but you still want answers



Detector simulations, What?

- There exists different level of simulation depending on what one wants to understand.
  - Low level precise simulation at the particle level.
  - High level parametric simulations considering a subset of parameters.
  - In-between, depending on what is the subject of interest.
- Keep aware of the fact that using a tactical nuclear weapon to kill a fly might be effective, all things considered, but a tad overkill.

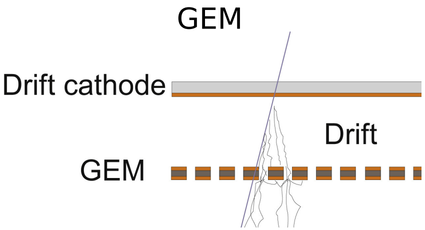
How?

- Write your own software
  - ☺ You have full control
  - ☺ You participate to the betterment of humanity by creating something new
  - 😐 If there is an issue it is on you
  - 😐 You need to understand a lot of things to make it work
  - ☹ It takes time to develop software
  - ☹ Often you might be the only person debugging it
- Use someone else software
  - ☹ You have limited control
  - 😐 If there is an issue you might spend some time wondering where the problem is
  - 😐 You need to understand a lot to understand the results
  - ☺ It is already written
  - ☺ Often the knowledge base is extensive and people are friendly

Case study: What are the signals generated by MIP muons passing through a Triple-GEM detector?

What is a Triple-GEM detector?

- Gaseous amplifier
- Low potential difference leads to high field if distance is short $E = -\frac{\Delta V}{\Delta x}$
- High field means charge production if initial ionisation



Why MIPs?

- If I can detect Minimum Ionising Particles, I can detect all the other ones

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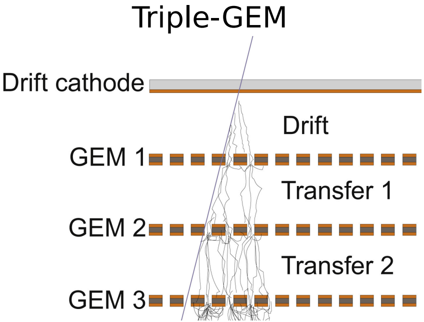

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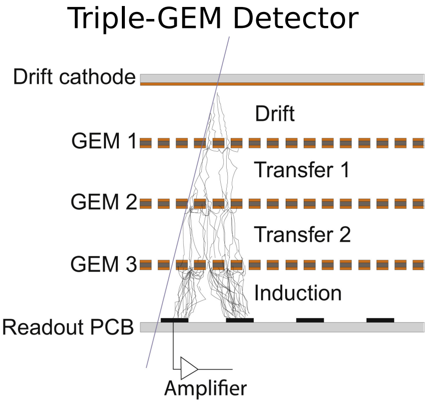
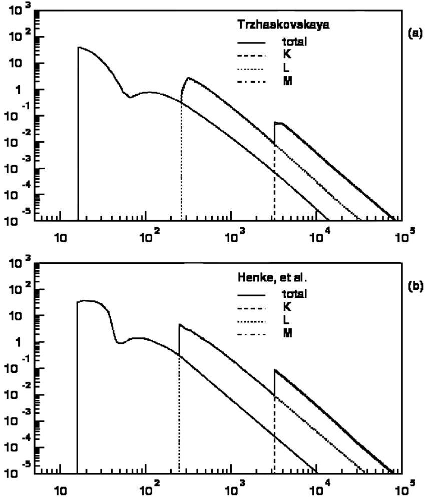


Why MIPs?

- If I can detect Minimum Ionising Particles, I can detect all the other ones

First Problem: What is the primary energy deposit in my detector?

- Average ionisation will not do, I need the actual ionisation
- What is the composition of my Gas?
- This is given by the Photon Absorption Ionisation (PAI(R)) model
- Short story: Ionisation can be devised by considering the target as a composition of nuclei "independent" from each other
- Rough approximation but the absorption lines of the medium tells you exactly how the energy exchange in-between the in-coming fast particle and the medium will occur because most of the electrons are bound in the medium



First Problem: What is the primary energy deposit in my detector?

Given by HEED++, simulation package developed by I. B. Smirnov

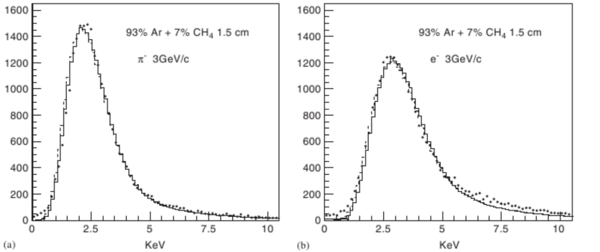


Fig. 3. The experimental (points) and theoretical "ionization loss" distributions expressed in energy units. Histograms drawn by solid lines are obtained by the PAIR model, dashed lines (they are practically coincide with solid ones) are by the PAI model.

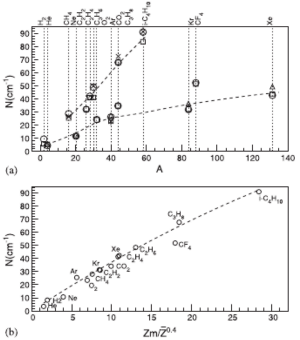
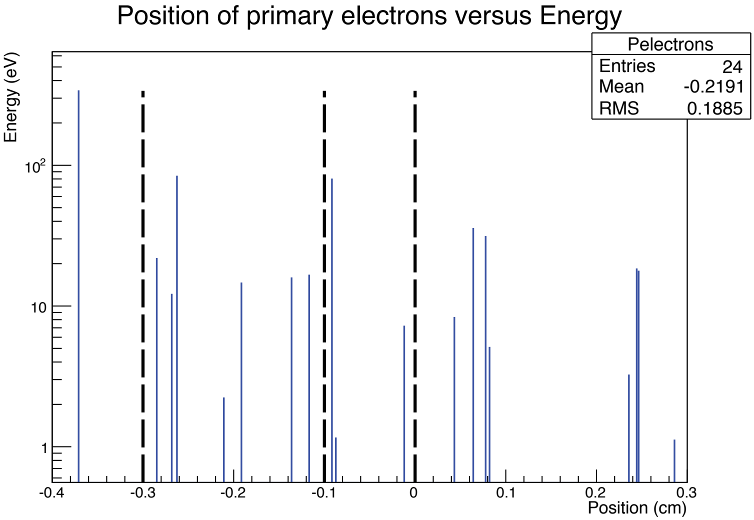


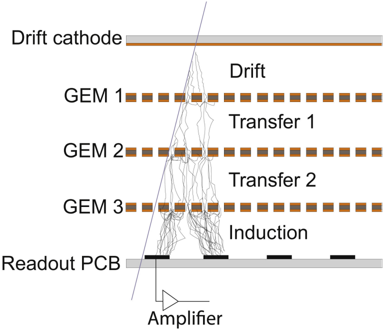
Fig. 2. The number of primary clusters for minimum-ionizing particles for various gases at NTP according to calculations by HEED (circles) and a number of measurements: Ref. [57] (squares), the average of numbers from Ref. [18] and seven other works quoted in Table 5 of Ref. [18] (stars), and Ref. [58] (triangles). (a) shows the dependency on the atomic or molecular weight. (b) shows the data of HEED only as function of $Z_m/\bar{Z}^{0.4}$. In (a) the dashed lines are drawn by hand to guide the eye. In (b) the dashed line represents fit to the given points except CF_4: $3.996x - 0.025x^2$ ($x = Z_m/\bar{Z}^{0.4}$).

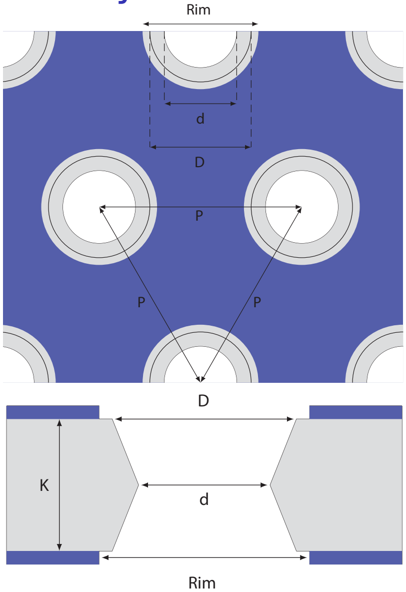
First Problem: What is the primary energy deposit in my detector?



Second Problem: What is the field in my detector?

- ➢ What is the exact geometry of my detector?
- ➢ Geometry of conductors will define the field inside the detector





How to use a TCAD software / FEM solver

1. Build your geometry through scripting and simple shapes
2. Define each element in your geometry by their dielectric constants(Bonus question: How would you define the dielectric constant of a gas you do not know?)
3. Generate Mesh (Usually the software is nice enough to do it for you)
4. Set boundary conditions
5. Start the solver and go get a coffee it can take time
6. Get the solution map and mesh map the material maps

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5. Start the solver and go get a coffee it can take time
6. Get the solution map and mesh map the material maps
7. Enjoy cocktails with supermodels by the pool basking in the wealth generated by your super precise use of computational tools [1]

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[1] Might be subjected to regional restrictions, as well as personal preferences... Though it will probably not happen...

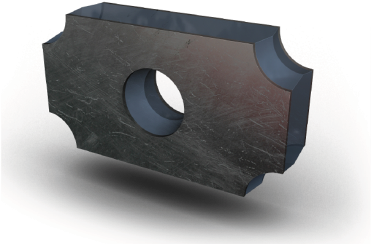
Building Geometry

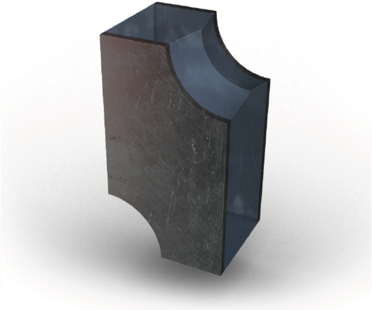
Concerning building your geometry...

Be smart!

Be like Noether and embrace symmetries!

The practicality of this is because you simulate less things and make it more efficient





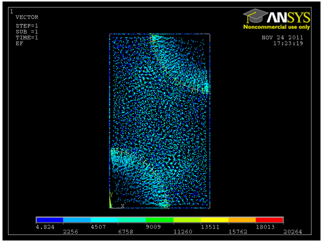
General advice on FEMs

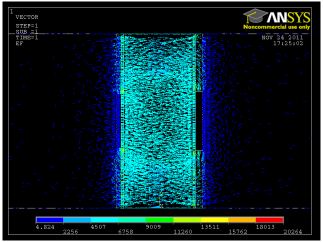
Always check your results!

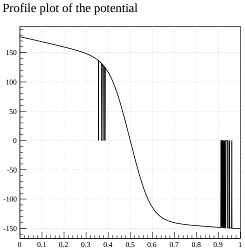
- FEM programs are efficient but can have some singularities in case of issues!
- FEM are slave to the meshing, and can impact field simulation precision!
- This can potentially lead to issues down the drain when you check your results
- If possible check the implementation of the code it's pretty fun is you can see how it is done, there are not only commercial options![2]

[2] Check some of those software and play with them!
https://en.wikipedia.org/wiki/List_of_finite_element_software_packages

Here is what one get for a very simple simulation





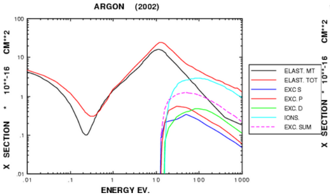


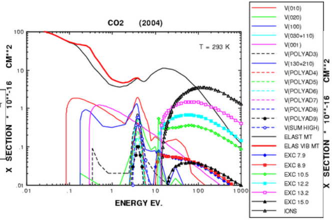
Charge propagation, where do they go?

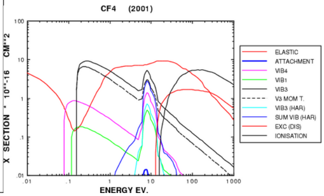
- We already briefly talked about the fact that charges can move in weird ways in detectors in general.
- But how would you propagate a particle if you were left free?

Charge propagation: Magboltz, Garfield

1. Move by a step given by the mean free path
2. Check which molecule we interacted with, rand[0,1]
3. Check which interaction one went under by looking at the cross section table
4. Update particle lists
5. Rince and repeat







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Quick question for you people

What is the mean free path of a particle?

$$\lambda \approx \frac{1}{n\sigma}$$

$n \equiv N/V$ density

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But...

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But...

$$\lambda_{(E)} \approx \frac{1}{n\sigma_{(E)}} \; \mathbf{!}$$

Metal Gear?!

$n \equiv N/V$ density

Quick question for you people

What is the mean free path of a particle?

$$\lambda \approx \frac{1}{n\sigma}$$

But...

$$\lambda_{(E)} \approx \frac{1}{n\sigma_{(E)}} \,!$$

Thus we don't know exactly what is the mean free path at each time step...

$n \equiv N/V$ density

Solution?

Add to the total cross section a probability of NOT interacting

$$\sigma_{\text{Eff}} = \sigma + \sigma_{\text{Null}}$$

- Technically reduces the stepping
- Check if the collision was efficient, if not, continue as if nothing happened
- If collisions was efficient → Interact with respect to the relevant process
- Rince, repeat

This is called the Null collision technique![3]

[3] https://www.sciencedirect.com/science/article/pii/0010465578900905

So far I have

- Field in my detector
- Incoming particle creating ionisation
- Propagation of charges in the detector

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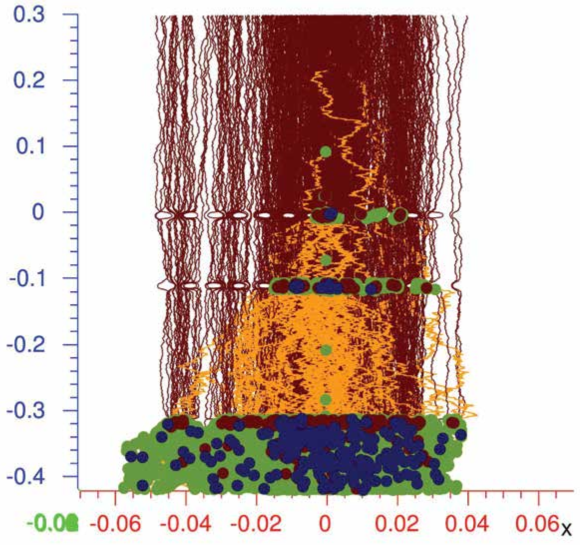
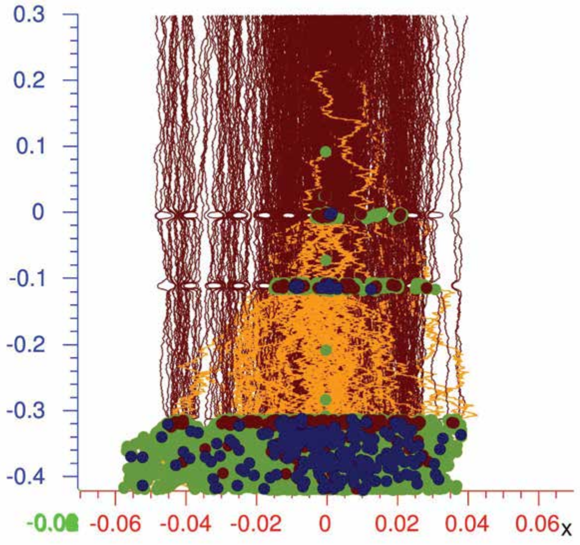
What happens when you put all of this together?

Glorious colours!



Glorious colours!

You get something really ugly, colour wise, but beautiful simulation wise

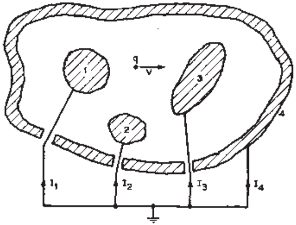


What is the signal created in my detector: Shockley–Ramo

$$I_i = E_v q v$$

In short: if you pass equi-potential lines, you will produce work, that work moves the charges, and those charges will rearrange to have no field in any conductor

In practice, put the conductor where I want the current to 1V and ground all the others



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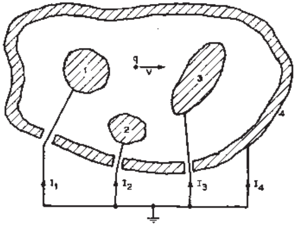

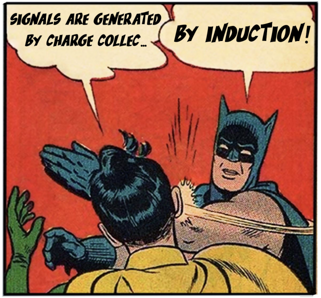

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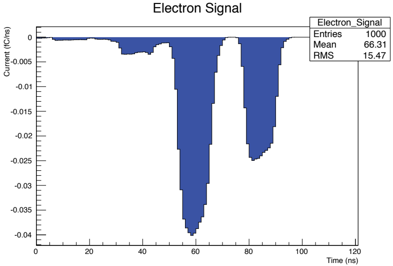
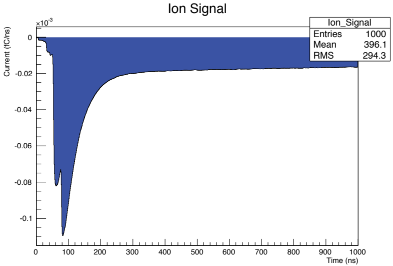
What do I do if I want my signals?

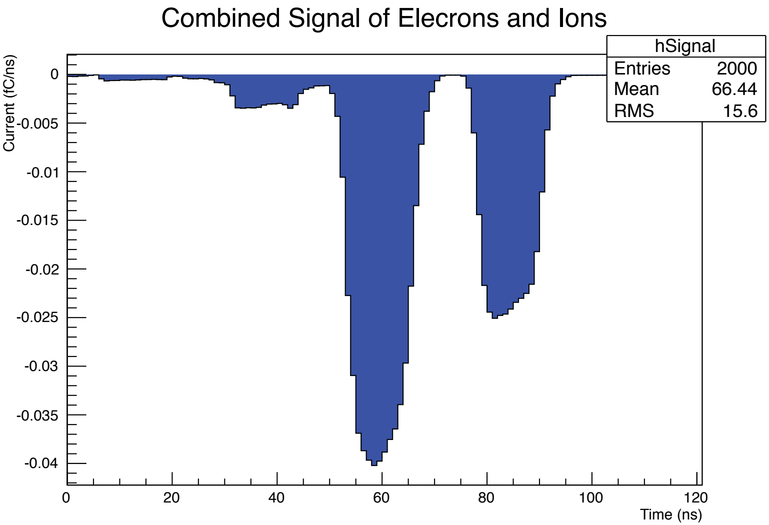
1. Take the previous mesh
2. Clean solutions on the mesh
3. Get my new exciting boundary conditions (1V on a conductor 0V on all others)

I can combine everything (again) and find this





If I look at the combined signals



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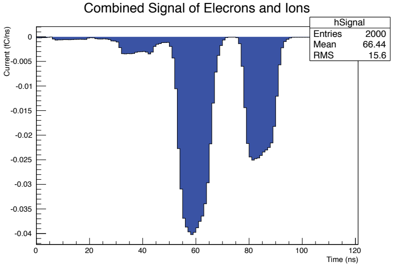
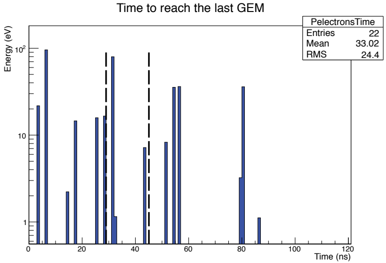
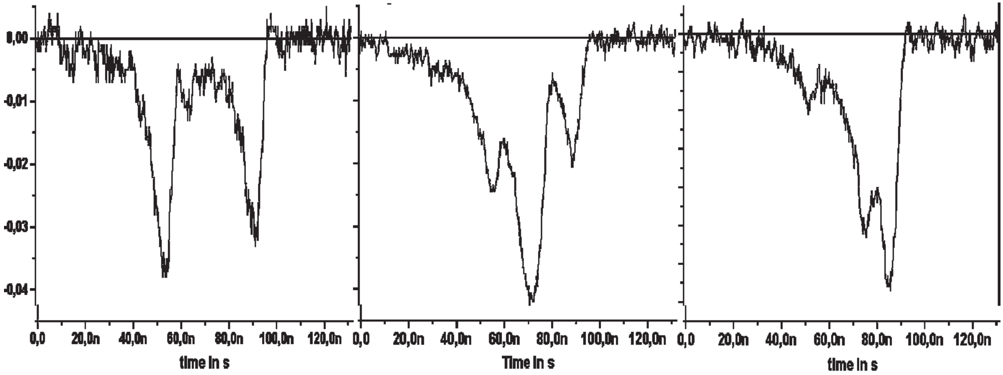




Does this correspond to reality?



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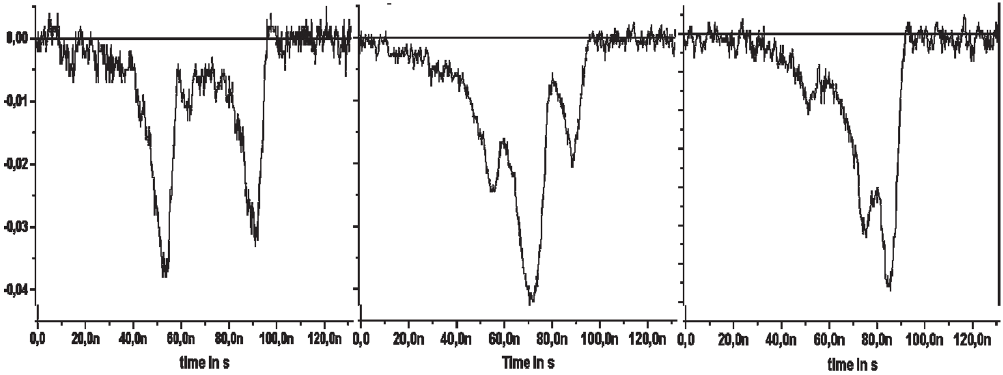

Nailed it.

What's missing though?

- Ion feedback
- Attachment (There but didn't mention it)
- Penning effect (There but didn't mention it)
- GEM Charging up
- Uncertainties in the GEM manufacturing
- Magnetic field effect
- Particles coming at an angle
- Multiple electrode effects
- Electronics behind the detector

What else is there?

https://garfieldpp.web.cern.ch/garfieldpp/ → What I used in this presentation

https://project-allpix-squared.web.cern.ch/project-allpix-squared/

http://www.fluka.org/fluka.php

https://geant4.web.cern.ch/ → You should all know something about this one

References

http://rjd.web.cern.ch/rjd/cgi-bin/cross?update

http://www.solid.unito.it/RICERCA/IBA/paper/Shockley_Charge_JAPL_1938.pdf

NUMERICAL RECIPES The Art of Scientific Computing Third Edition, I usually wont tell people to go buy books, well I do, but if you do buy one, consider this one http://numerical.recipes/

https://www.comsol.com/multiphysics/finite-element-method

https://indico.cern.ch/event/391162/

Most of the things you might have wanted to know about detectors* (*But were afraid to ask)

Part 3

What lies behind the detector?

Geoffrey Mullier

PIER, 25th September 2019

Partnership of Universität Hamburg and DESY

We have seen that

- Detectors are all about moving charges.
- Those moving charges induces current on conductors.
- These currents will be the data that we want to interpret.

What type of electronics stand behind the detector

- Read-out electronics
  - Configuration of the on board electronics
  - Getting the data out from the on board electronics
- Powering electronics
  - Giving power to all the on board electronics
  - Making sure no one dies while the detector is operating
  - Making sure the detector doesn't commit suicide

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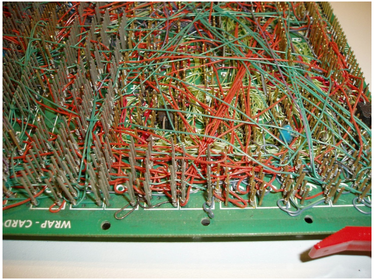
You might have interplay between both of those things

Read Out Electronics

- Every single piece of modern detector is connected to a piece of electronics
- Varies in function of the use, but there are some components that are not changing much

Printed Circuit Board (PCB)

➢ Printed circuit boards are circuits in very compact form of wiring electronical components together



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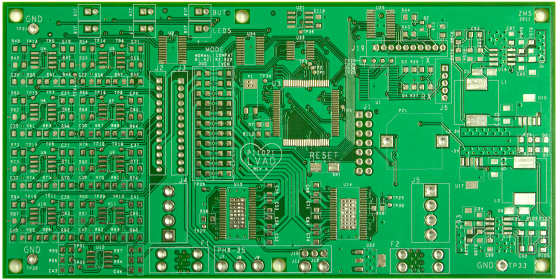
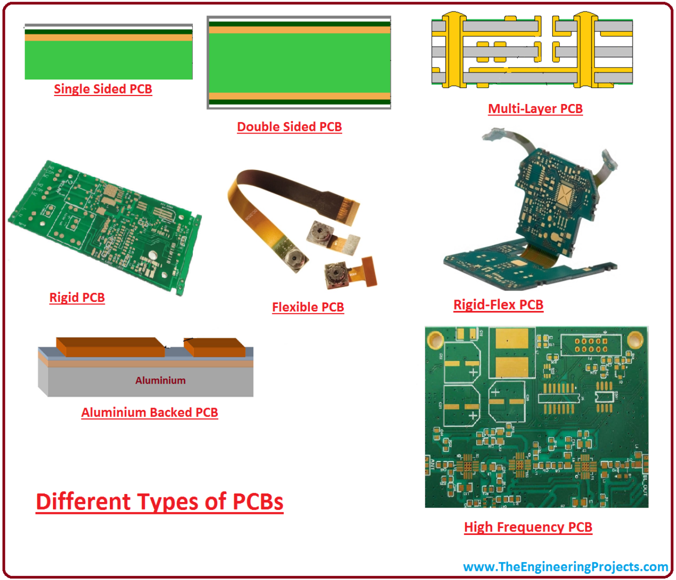
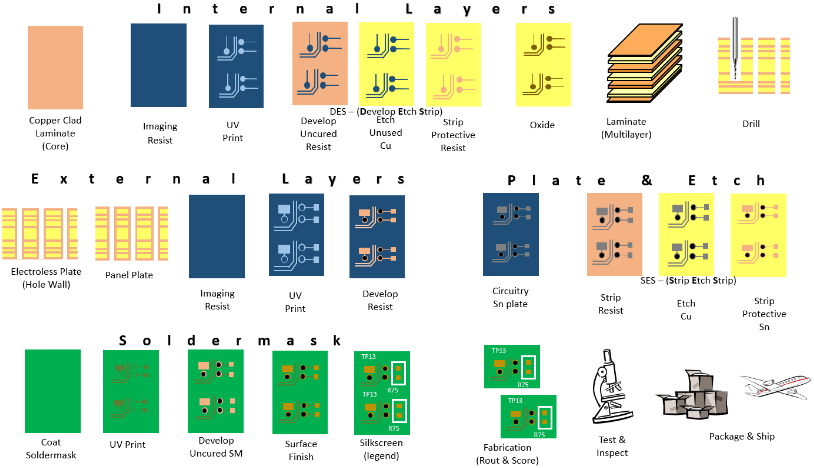


https://www.palpilot.com/pcb-101/

PCB Types


Single Sided PCB
Double Sided PCB
Multi-Layer PCB
Rigid PCB
Flexible PCB
Rigid-Flex PCB
Aluminium
Aluminium Backed PCB
Different Types of PCBs
High Frequency PCB
www.TheEngineeringProjects.com

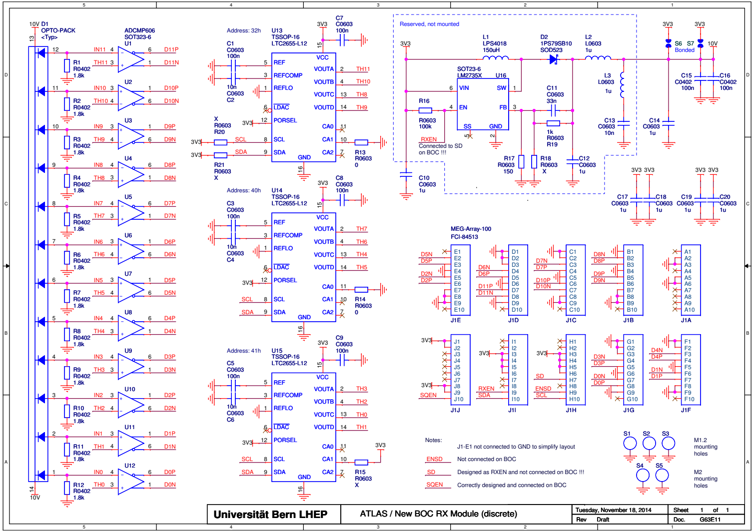
PCB Manufacturing



PCB Manufacturing: Defects?

- Incorrect impedance on trace
- Shorts on trace
- Shifting of components
- Corrosion
- Delamination
- ...

How to read a board diagram?



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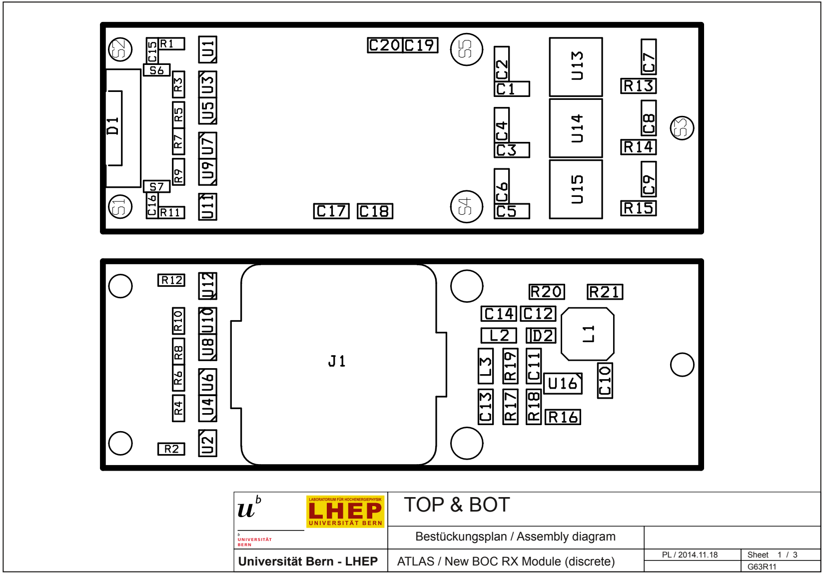
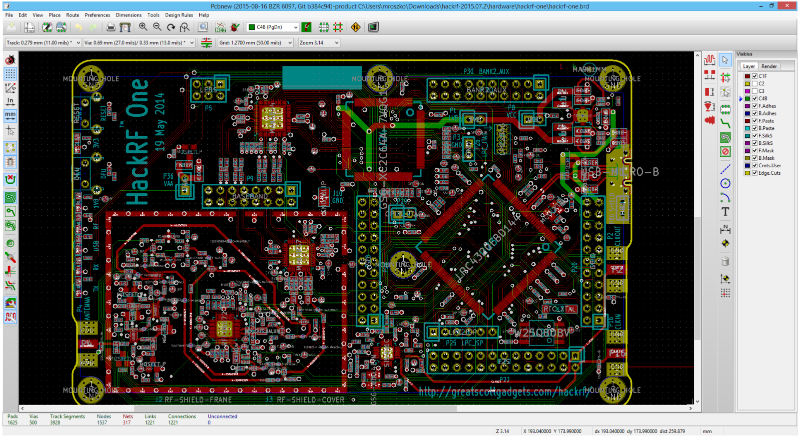


Want to try to design a PCB?

➢ Use a PCB editor like KiCad (Not advertising just an example)

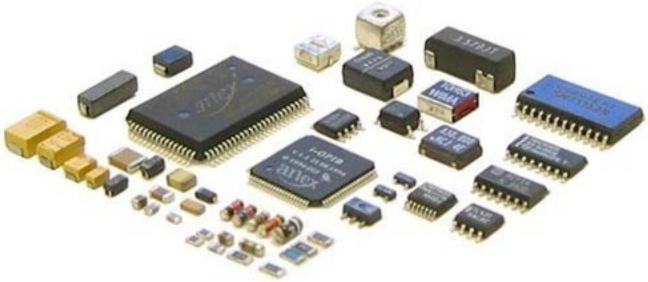


¿SMD IC ASIC FPGA? Wut?

- SMD: Surface Mounted Device
- IC: Integrated Circuit
- ASIC: Applicaiton Specific Integrated Circuit
- FPGA: Field Programmable Gate Array

SMD: Surface Mounted Device

- Resitor
- Capacitor
- Inductor
- Transistors
- ICs



https://youtu.be/VMyd0ydGNMA

Inerlude, what is the resistance of a 10kΩ resistor?

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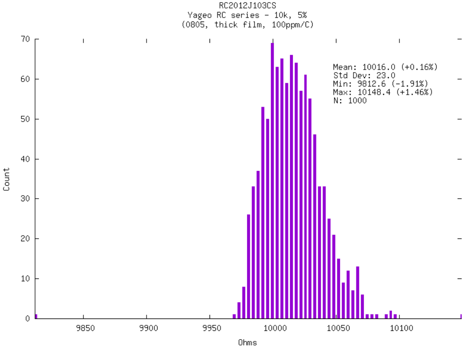

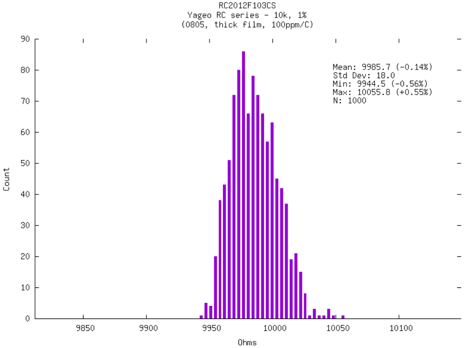

https://www.eevblog.com/forum/projects/smd-resistor-distributions/

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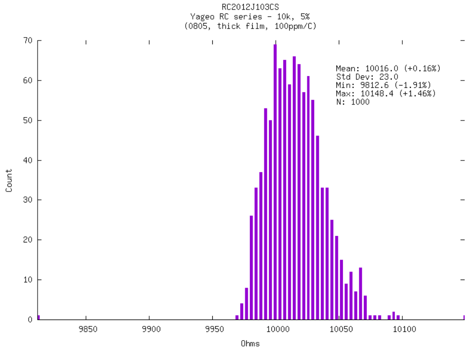
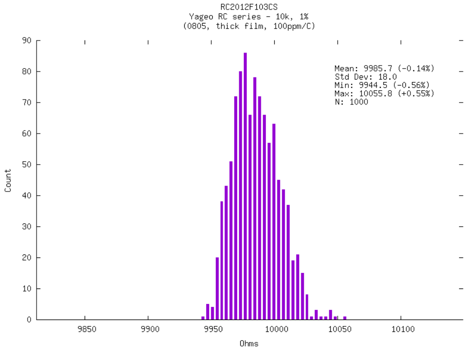


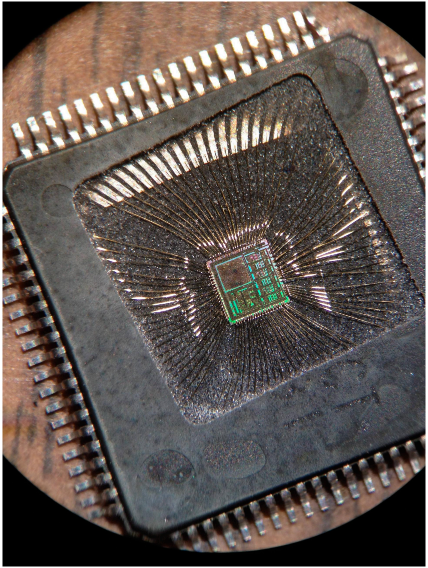


There is a spread in the distribution, this is perfectly normal but one needs to take this into account when designing!

https://www.eevblog.com/forum/projects/smd-resistor-distributions/

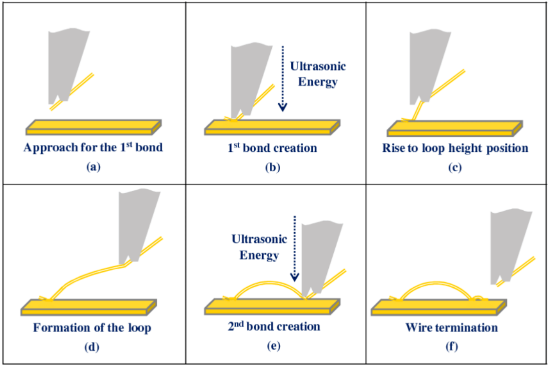
IC: Integrated Circuit

- Mass produced specific circuit
- Cheap and versatile
- Precise specifications telling you what exactly it is doing
- Can come either packaged for easy handling and mounting or non packaged for space concerns.
- Though in that case require wire bonding

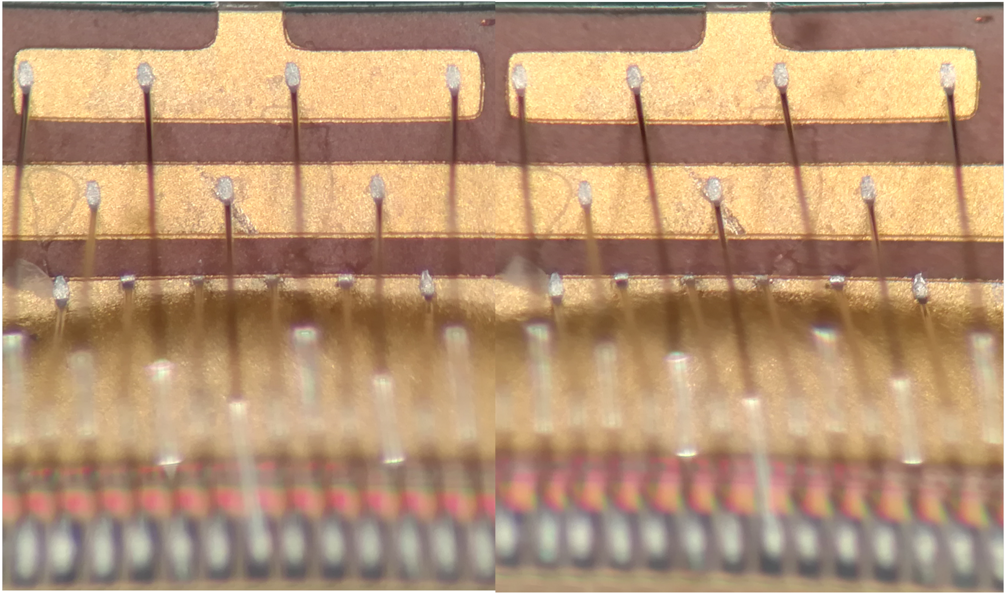


Wire bonding what is it?

- ➢ Connecting pads to other pads via thin wire
- ➢ Physics of very tiny and thin materials is tricky!
- ➢ Surface composition and wire deformation plays an essential role at getting it right

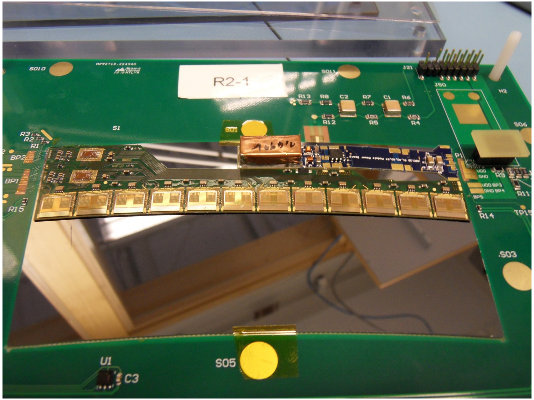


How does it look like?



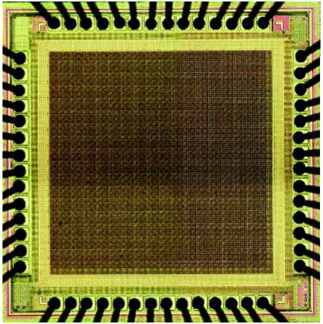
ASIC: Applicaiton Specific Integrated Circuit

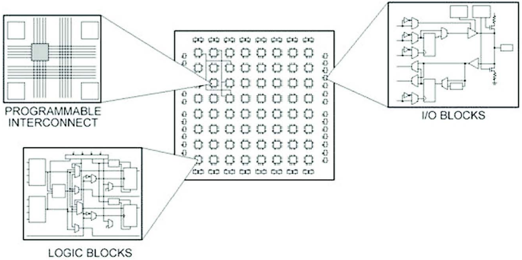
- Completely custom integrated circuit
- Expensive to design, cheaper to produce once designed



FPGA: Field Programmable Gate Array

- Completely re-programmable IC
- Used normally in prototyping and replaced by either a specific ASIC or combination of ICs if possible
- In HEP used because both convenient and ability to expand functionality after first commissioning





How to Program a FPGA?

- Verilog Hardware Description Language (VHDL)
- You do not compile it you synthesise it
- C# interpreter possible
- Should be thought of as designing a PCB/circuit
- A FPGA is NOT a CPU

https://www.allaboutcircuits.com/technical-articles/hardware-description-langauge-getting-started-vhdl-digital-circuit-design/

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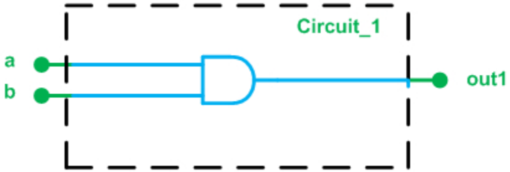
How to Program a FPGA?

```
entity circuit_1 is
    Port ( a : in  STD_LOGIC;
           b : in  STD_LOGIC;
           out1 : out  STD_LOGIC);
end circuit_1;
```

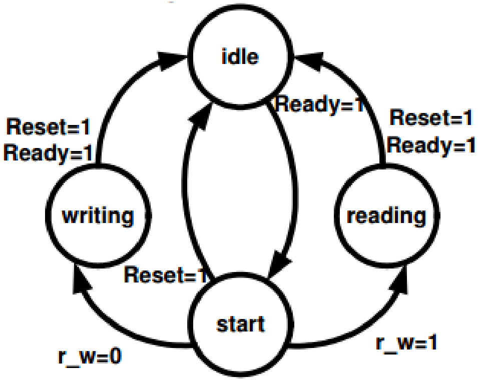
```
architecture Behavioral of circuit_1 is
begin
out1 <= ( a and b );
end Behavioral;
```



Finite State Machine (FSM)

Every single piece of Digital electronics is an FSM one way or the other
(including your computers and phones)

- An FSM is a collection of state
- And one can transition from one to the other on some conditions



Analog Vs Digital

In super short

$$[0,1] \leftrightarrow \{0,1\}$$

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Discrete set of signals that can be modelised with Boolean logic
Continuous signals which have a harder time with Boolean logic

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Digital to Analog Converter (DAC) $\leftrightarrow$ Analog to Digital Converter (ADC)

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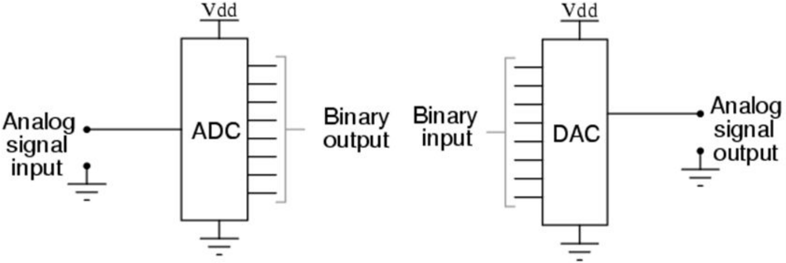

Reminder RLC

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Every circuitry can reduce itself to small minimal working blocks

Each of those blocks might have different quirks and nominal frequencies or operation weirdness

All electronics ever devised was designed to work in a certain frequency range

Stay aware of this at all times

non return to Zero / DC neutrality

One says that a system is DC neutral if it has the following property

$$\lim_{T\to\infty} \frac{1}{T}\int_0^T V(t)\mathrm{d}t = 0$$

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Why does that matter?

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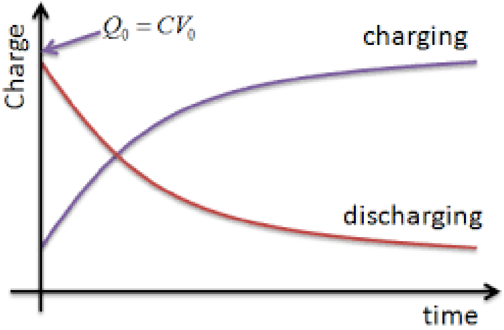


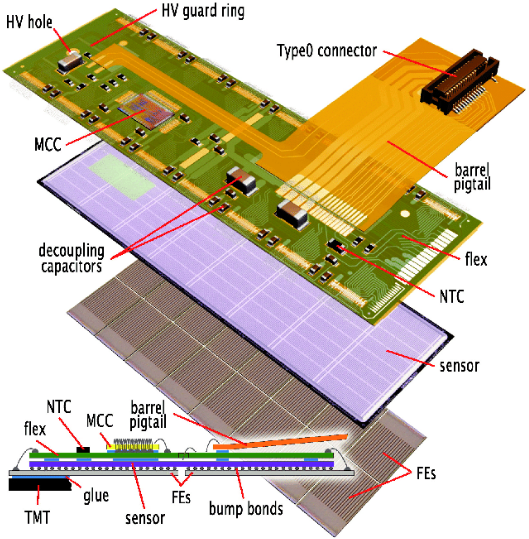
Everything is an antenna

"The only thing harder than making something radiate really well is to make it radiate not at all."

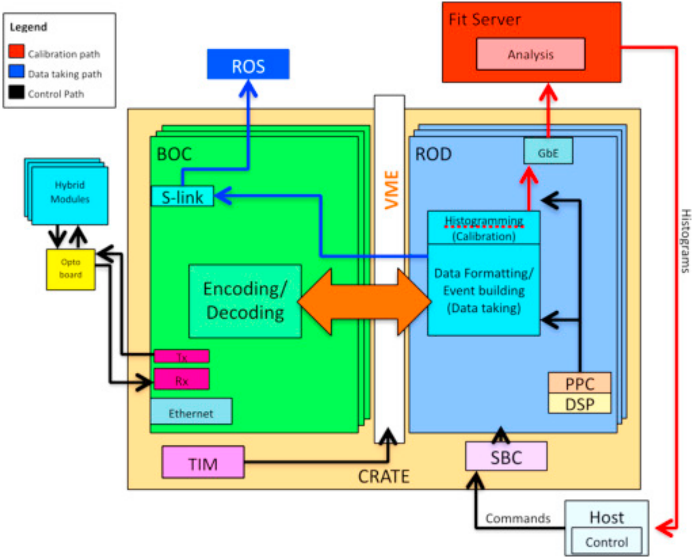
Your electronics will pick up noise from the environment

Think carefully when treating with this

ATLAS Pixel Module



ATLAS Pixel readout structure



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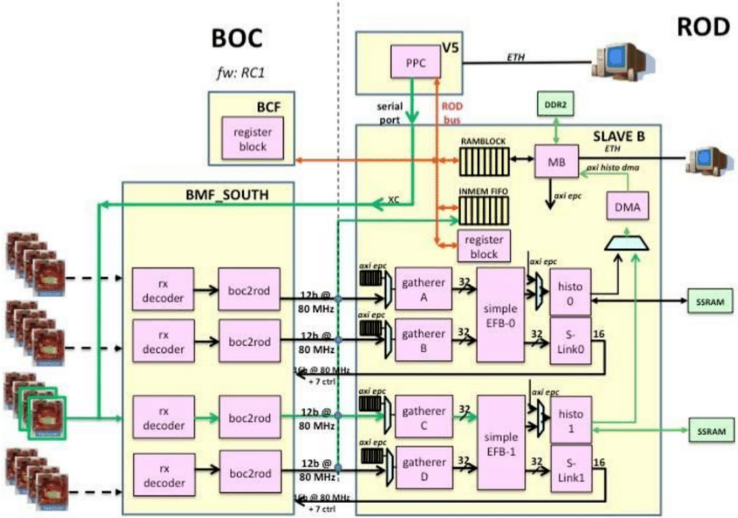

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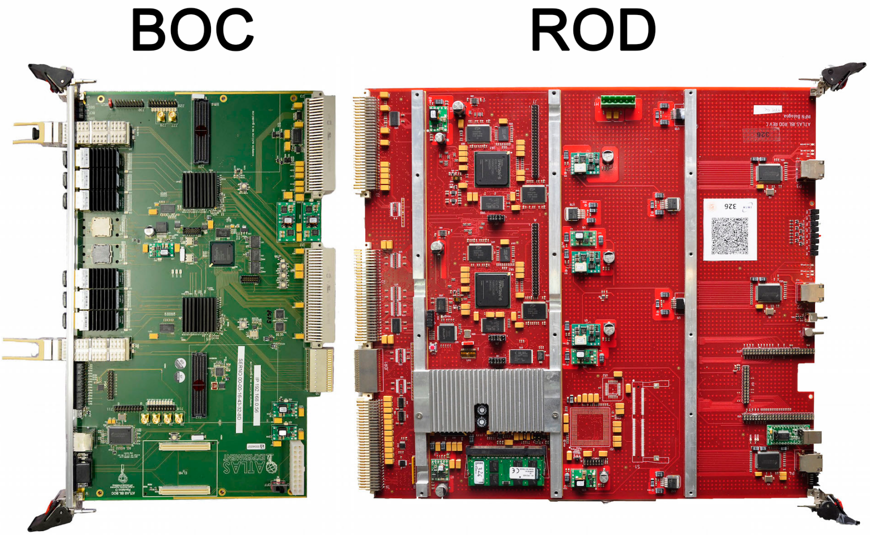


Most of the things you might have wanted to know about detectors* (*But were afraid to ask)

Part 4

The unsaid

Geoffrey Mullier

PIER, 26th September 2019

PIER

Partnership of Universität Hamburg and DESY

Lund University

Since it is after the official school dinner...

You must have had a long night yesterday...

And this day has been difficult so far...

But this is the afternoon...

So the hungover should have worn off...

But it is the last day...

You start to get tired, so...

Let's get started!

This lecture is really non-linear

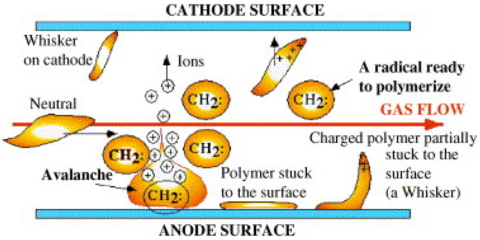
- And not really a lecture, this is more a compilation of different advice, tips, tricks that I wished people told me or insisted on at an earlier time in my career.
- This section is highly experimental so buckle up kids
- Let's get started

Detector performance

- Detectors will have extremely high varying performances depending on the metric one looks at and can depend on
  - Geometry
  - Electronics
  - Environmental conditions
  - Data Acquisition code
- Use and design the tool for the job and do not design the job for the tool

Ageing of detectors

- ➢ Usually people do not like to mention the fact that they age, and their detectors do too
- ➢ Detector ageing is a really complex topic and usually poorly understood for the most part because it relies on technicalities of the detector considered in general
- ➢ Following link focused on gaseous detectors http://www.desy.de/~agingw/preprints.html
- ➢ Extensive knowledge on solid state detector available for radiation damage in general.



Time scheduling

- Never, ever under estimate the time required to do something
- Whatever time-frame you might think about, take it, multiply it by two and add one month
- There will be unexpected delays
- You will be waiting for other people
- Nothing will ever work the way that you want

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- Nothing will ever work the way that you want
- but...

Time scheduling

If you have some time

- Think about the process, identify tasks, make a list and try to foresee what might go wrong
- Organise your time accordingly but be flexible depending on the project
- Do everything as early as possible to save yourself from unforeseen consequences

If you have no time

- Think about the process, identify tasks, make a list and try to foresee what might go wrong
- Get working on the most urgent item on your list
- Take things one at the time systematically, stressing over it will not make things better, only worse

Trying and failing is OK

- No one ever succeeds on the first try
- If they do they might not be prepared for failure
- Things will break, though one must work as to try to break as little things as possible...

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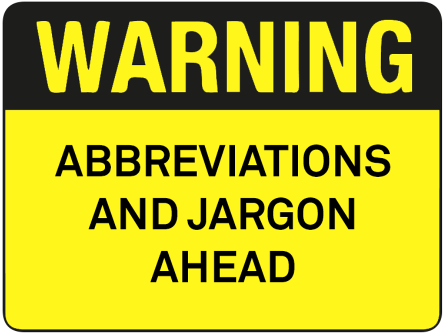
- but...

Abbreviations and Jargon

- Minimise the use of them (We absolutely fail on this in ATLAS and HEP in general...)
- If you have to use them, make sure they are defined
- They are supposed to exist in order to make people life easier not harder!



Abbreviations and Jargon : The must know

RTFM	Read The Fucking Manual
WTFM	Write The Fucking Manual
KISS	Keep It Simple, Stupid
PEBKAC	Problem Existing Between Keyboard And Chair
FUBAR	Fucked Up Beyond All Recognition
SNAFU	Situation Normal All Fucked Up
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Abbreviations and Jargon

- List all the abbreviation you come in contact with and share them
- Do not hesitate to put them around
- Two websites that are useful in general
- http://maalpu.org/lhc/LHC.abbrs.htm
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/WorkBookGlossary

The must do in the lab

WRITE EVERYTHING DOWN!

- You **WILL** forget things, and recovering from something forgotten takes usually much more time than normally.
- In addition writing things down help you track and debug things more clearly

READ EVERYTHING SEVERAL TIMES!

- You **WILL** misunderstand things, and misunderstanding can lead to damages to equipment, yourself or others

DO NOT ASSUME!

- Be certain, take your time when doing something

Keep things organised as much as possible

WRITE EVERYTHING DOWN!

- You **WILL** forget things!

YOU WILL GAIN TIME BY LOSING SOME AT AN EARLIER TIME

- **DO NOT** hesitate to lose time organising things, this is an essential part of actually doing work in a lab

KEEP ANY COMMON WORKING SPACE CLEAN AND ORGANISED

- Honestly it will make everyone life easier

Concerning using other people things

NEVER USE A BLACK BOX!

- Understand your tools to be able to know exactly what you can get away with
- This goes for physical items and software
- If you do not, this **WILL** be your downfall

IF IT IS A TOOL FROM A WORKSHOP

- **PUT THE TOOL BACK**, I do not care, the engineer does not care and the technician you probably nicked it from does not care what your excuse is, it is probably not valid anyway

Do not hesitate to get your hands dirty

- Touching a detector is OK...
- ...As long as you know what you are doing
- Do not hesitate to ask and seek the ones that know

Absolutely everything is flawed in a way or another

- This goes for every piece of hardware you will ever own
- This goes for you, your lovers, your family, your friends and your colleagues, we are all humans
- This also goes for every detector ever devised
- But that is OK
- Learn the quirks of everything you come in contact with and make the best of it
- But do not forget that the demon is always in the details!

This goes for everything

INCLUDING THE FUCKING MANUAL!

- If you have a doubt, double check it

INCLUDING THE EXPERTS!

- People are human and sometimes do mistakes
- Be aware of that fact and work with it, not against it.

DO NOT ASSUME!

- Be certain, take your time when doing something

Coding

DO NOT TRY TO BE CLEVER!

- Any attempt to be clever always end up with you, in the future, wondering why or how the hell you thought this was OK.
- Think before implementing something but do not think too long either start on paper and go from there
- In most of the cases the compiler is smarter than you[1]

WRITE CLEAR AND COMMENTED CODE!

- Any piece of code you write should have
  - Useful comments (I will metaphorically bash your head in if you tell me that your code is self documenting)
  - Human readable variables and methods names
- At some point either you will be the one dealing with your mess or someone that is going to hate your guts

[1] Well... sometimes it is pretty much not...

Coding

GLOBAL VARIABLES ARE GLOBALLY BAD!

- Seriously there is use for it, but in most of the cases you can do without.
- Even if you think this not to be true, it is.

DO CHECK THAT YOU DID NOT MISUNDERSTAND WHAT PEOPLE ASKED

- It is so very easy to misunderstand something, confirming that you understood exactly what was happening is essential

Debugging hardware or software

DO NOT ASSUME!

- The error is always in what you supposed was fine
- Debug step by step and **DO NOT SKIP** a step
- "When you have eliminated the impossible, whatever remains, however improbable, must be the truth."

ESTABLISH MINIMAL WORKING BLOCKS!

- Be it in hardware or software, go back to the basics and work your way from there
- Testing units help you move forward in design and implementations
- It is like building Legos, except it is not Legos, and then you do not get a cool looking spaceship at the end...

Debugging relationships

LEARN TO APOLOGISE!

- This goes a long way to recognise that you were wrong
- And it helps becoming both a better physicist and person

COMMUNICATE!

- 90% of the issues that are encountered with something due to miscommunication or misunderstanding
- Sometimes it can be hard, but do an effort to meet people in the middle

Useful tips

rsync -azP user@host:/origin/directory user@host:/target/directory

nmap -sP 192.168.100.0/24

.ssh/config

.bash_rc / .bash_profile

which cmd

find . -iname '*WhAtEvEr*.eXt'

ln -s /path/to/file-name link-name

screen/nohup/tmux

htop

brew (Mac crew)

Putting it very basically

In the words of Hollywood Superstar Shia Laboef...

Putting it very basically

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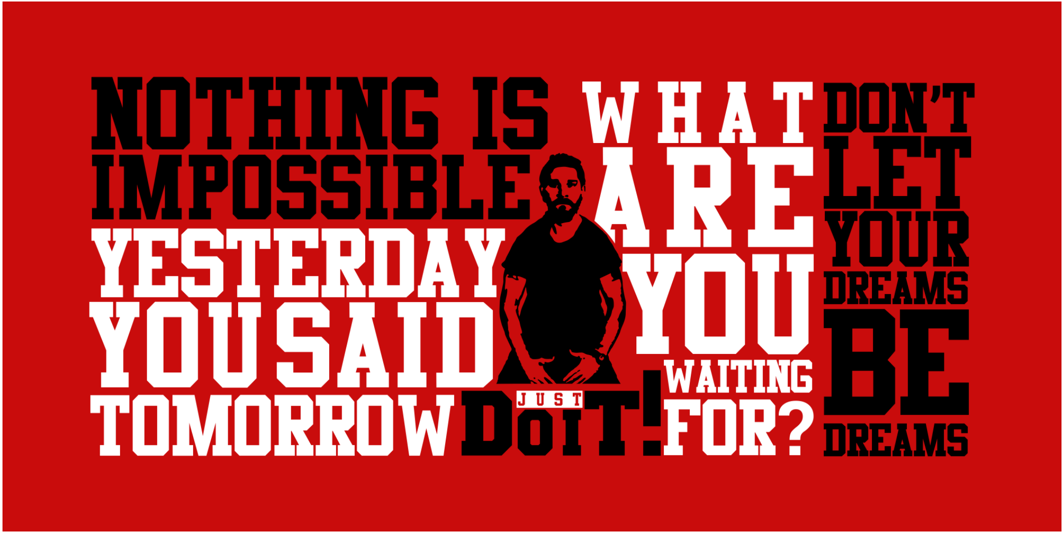


A few concluding words

"[...] The worthwhile problems are the ones you can really solve or help solve, the ones you can really contribute something to. A problem is grand in science if it lies before us unsolved and we see some way for us to make some headway into it. [...] **No problem is too small or too trivial if we can really do something about it.**[...]"
Richard Phillips Feynman, letter to Koichi Mano.

"**Ever tried. Ever failed. No matter. Try again. Fail again. Fail better.**"
Samuel Beckett

A few concluding words

Whatever happens,
Just do things right,
Do not cut corners,
Do not be a dick to others,
Remember everyone is human,
Do not forget to have fun.

I thank you all for enduring me until now...

Most of the things you might have wanted to know about detectors* (*But were afraid to ask)

Part 1

General concepts

Geoffrey Mullier

PIER, 23th September 2019

First, a disclaimer...

- It is the first time that I do this type of lectures, apologies if it is rough around the edges
- If did not include your favourite detection technique
  ↳ Sorry
- If I misrepresent your favourite detection technique
  ↳ Sorry

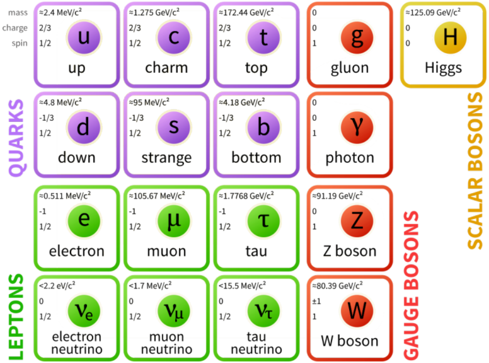
Second, the rules...

- At anytime if you have a question
  - ↳ Ask! (but remember that you can either email me or contact me at anytime if you have additional questions or need additional informations, geoffrey.mullier@cern.ch)
- If you spot a mistake
  - ↳ please let me know, nobody's perfect!
- The course is starting everyday at 5min past the "official" starting time, consider this the academic quarter (so you can roll in from lunch after stuffing yourselves, I know I will).
- The course is meant to have interruption of 5 min every $\pm$30 min or so.
- At the end of every course, 15 mins are dedicated only for discussion.
- This course was written with the primary goal to give you clues to where to look or general ideas, not meant to be the ultimate bible of knowledge.

What the hell are we talking about here?

Standard Model of particle physics

- Lagrangian describe interactions for three of the four fundamental forces of nature.
- In general, want to test the validity of the Lagrangian.
- Need to measure the parameters of the SM: Masses, couplings, mixing angles...



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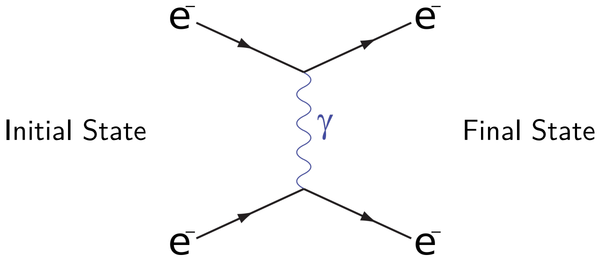
What is a measurement?

Not easy to answer in general

- Depending on whom you ask, the definition of measurement can be difficult to make (Ask your friends doing quantum information)
- Though for all intent and purpose we will define it as identifying the final state of a system (particle types, momenta)
- We want P_i^μ of all outbound particles (NB My time flows from left to right unless stated)

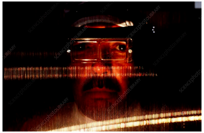
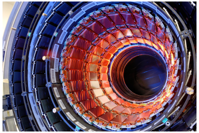
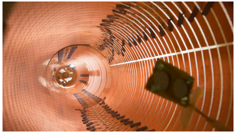
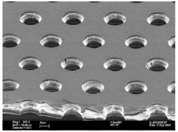


How on earth do we measure interactions?

I spoiled it a bit, but, short answer is: We do not

- We always measure secondary products of the interactions
- Secondary products, if stable enough, will interact with your detector
- The interaction that we can measure with the detectors are electro-magnetic (we are going to get back to this in a moment)
- There is no way to tell exactly what a single event was, the best one can get is a candidate final state that would correspond to the process one want to consider.
- One has to make counting experiments to see if it does correspond to what one was expecting or not

What type of detectors exists?

MWPC	Drift Tubes	Pixels	Cherenkov
GEMs	TPC	Planar	Geiger counter
RPC	Calorimeters	3D	Scintillator
CSC	Silicon detectors	HVCMOS	PMT
MicroMegas	Strips	Transition Radiation	SiPM
TGEMs	Bubble chamber	Cloud chamber	Monolithic Pixels

In short... LOADS!

Though most of those abbreviations or terms are actually a variation on very basic principles/a different design for same detection principle

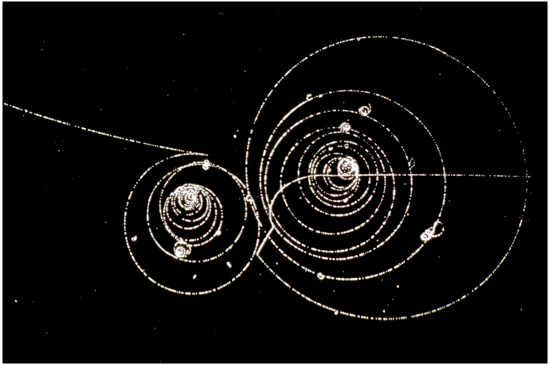
What does matter in particle detection?

Detection : Is it there or not?

Measurement : If it is there, what energy/what momentum?

for particle of charge q with momentum p in a field B

$$R = \frac{|p|}{qB} = \frac{\gamma\beta mc}{qB}$$



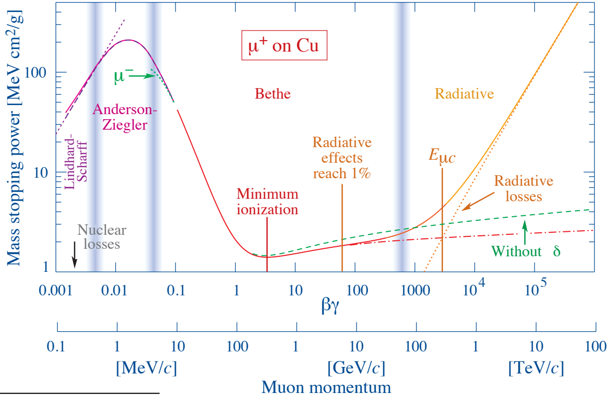
How to detect a particle

By its energy deposit in the medium it passes through

- Charged particles
  - Ionization of atoms
  - Excitation of atoms
  - Bremsstrahlung (only relevant for electrons and positrons)
  - Cherenkov radiation
  - Transition radiation
- Photons
  - Compton effect
  - Pair production

Bethe-Bloch equation: average energy loss in medium

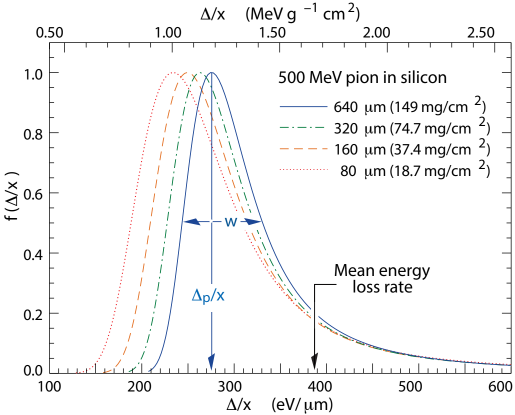
$$-\left\langle\frac{dE}{dx}\right\rangle = Kz^2\,\frac{Z}{A}\,\frac{1}{\beta^2}\,\left[\frac{1}{2}\ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2}\right)-\beta^2-\frac{\delta}{2}\right]\;;\;K\equiv\frac{4\pi}{m_ec^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2$$



⚠ only applies for average in the $0.1 \leqslant \beta\gamma \leqslant 100$

Lund University

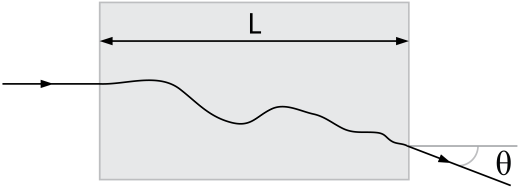
Landau-Vavilov: Variation of energy deposit for thin targets



Instantaneous deposit of energy is different than average

Not an easy problem to tackle since it does take into account the medium

Multiple Scattering



- Interaction with the target nucleus follows a Coulomb scattering
- Can repeat itself, causing multiple scattering of the particle in the target
- Deviation of θ_0 in the initial direction given by the following relation, expressed in X_0, radiation length

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

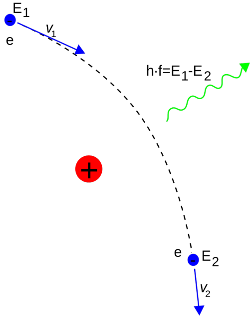
Only valid for small angles deviation, go see the reference for more infos!

Bremsstrahlung

If a particle interacts with the field of a nucleus, there is a probability to lose significant amount of energy by radiating a photon

This effect is called Bremsstrahlung and the probability depends on the mass of the incoming particle

$$P_{\text{rad}} \propto m^{-4} \; [1]$$



[1] Jackson, Classical EM 15.2

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Movements of charges in vacuum and gases (It's pretty useful to understand it in general)

Simple equation of motion of charges in an electric and in a magnetic field in addition of a friction term

$$m\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = e\left(\vec{E} + \vec{v}\times\vec{B}\right) - K\vec{v}$$

The average speed in the gas can be expressed as drift as components caused by the $\vec{E}$ and $\vec{B}$ fields[2]

$$\vec{v} = \frac{\mu E}{1+\omega^2\tau^2}\left[\vec{1}_E + \omega\tau\left(\vec{1}_E\times\vec{1}_B\right) + \omega^2\tau^2\left(\vec{1}_E\cdot\vec{1}_B\right)\vec{1}_B\right]$$

[2] With $\omega \equiv \left(\frac{e}{m}\right)|\vec{B}|$ and $K \equiv \frac{m}{\tau}$

Important elements from the previous solutions

$$\vec{v} = \frac{\mu E}{1+\omega^2\tau^2}\left[\overrightarrow{1}_E + \omega\tau\left(\overrightarrow{1}_E \times \overrightarrow{1}_B\right) + \omega^2\tau^2\left(\overrightarrow{1}_E \cdot \overrightarrow{1}_B\right)\overrightarrow{1}_B\right]$$

1 If no magnetic field is applied, the relation is linear, depends on the material via the coefficient μ which is called mobility, with respect to the electric field applied

$$\vec{v} = \mu\vec{E}$$

2 If there is both an electric and magnetic field applied one can see that the charge would drift in a direction which is a composite of the direction of the electric and magnetic field

Electrons instantaneous and average speed

$$v^2 = \frac{eE}{m_e N\sigma}\sqrt{\frac{E_{\text{Loss}}}{2}}$$

$$v_I^2 = \frac{eE}{m_e N\sigma}\sqrt{\frac{2}{E_{\text{Loss}}}}$$

Seemingly this is surprising, the instantaneous speed varies inversely with respect to the fraction of energy lost, whereas the average speed goes faster

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If the electron loses all its momentum at each collision it will only gain momentum in the desired direction, if it loses part of its momentum, it can travel back and hurt the average speed

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Note that those also depends on the cross section

Question of diffusion

- Diffusion can be less straight forward to understand (at least under external field and not due only to brownian motion)
- Depending on the orientation of the fields and drift direction diffusion can be limited
- This results in different diffusion coefficient, longitudinal and transverse
- The diffusion coefficient is often expressed in term of the drift length

$$D_d = \frac{\sigma_x}{\sqrt{z}}$$

N.B. I am considering here a well behaved gas, things can get way less obvious if the gas conditions are more exotic

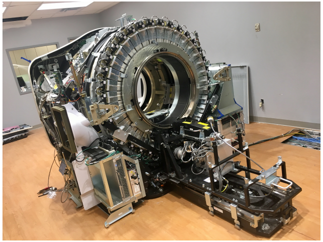
Where do you find detectors?

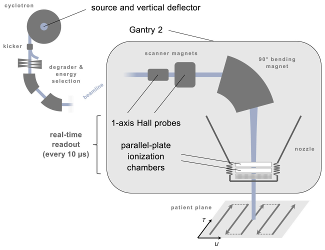
Your cameras → Silicon sensors

Hospitals → medical imaging (PET Scanner, beam monitoring for proton therapy)

Airport → X-Ray machines

Research institutes → from single photon counter to high fluence environment.





The original detector : photography plate, silver halide based

- ➢ Sensitive to visible light, but not only
- ➢ Excellent resolution, limited by grains sizes
- ➢ Does not require any power
- ➢ No timing information
- ➢ Requires developing the film

$$\mathrm{Ag}^+ + \mathrm{Br}^- + \gamma \rightarrow \mathrm{Ag}^+ + \mathrm{Br} + e^-$$
$$\mathrm{Ag}^+ + e^- \rightarrow \mathrm{Ag}$$

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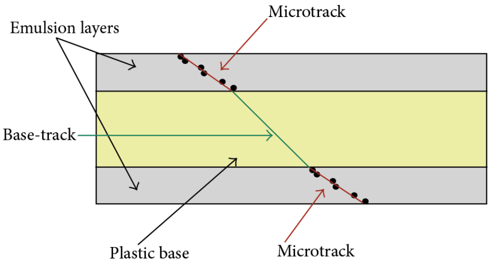
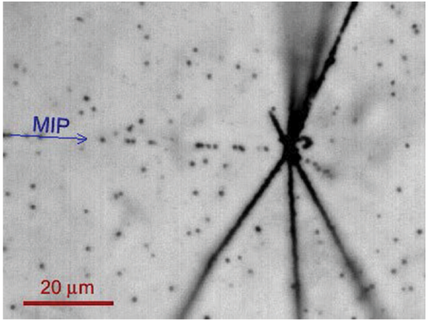
$$\mathrm{Ag}^{+} + e^{-} \rightarrow \mathrm{Ag}$$

Nuclear Emultions : Same as photography plate, spiritually

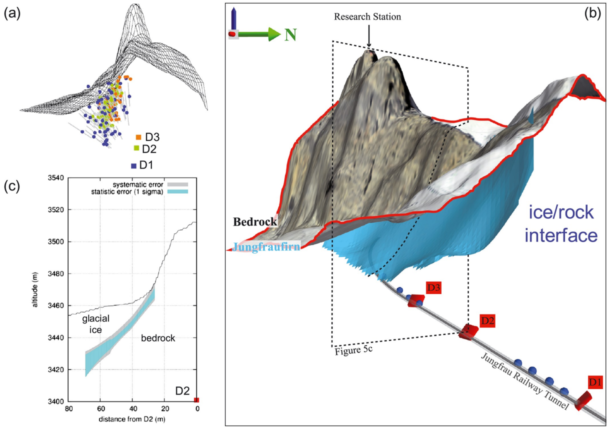
- Except you stack a large number on top of each other
- Require long time scanning surface for reconstructing particle tracks
- Unparalleled spatial resolution, can be equivalent to a voxel size of 0.125 μm^3

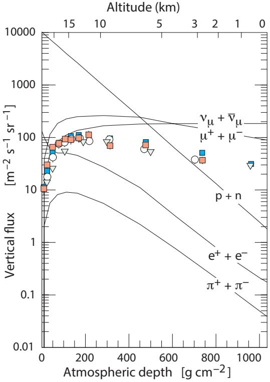


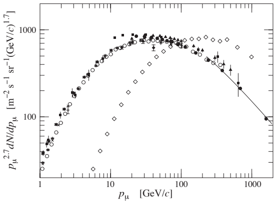
AEgIS Proton annihilation



Nuclear Emultions : Cool application, Muon tomography







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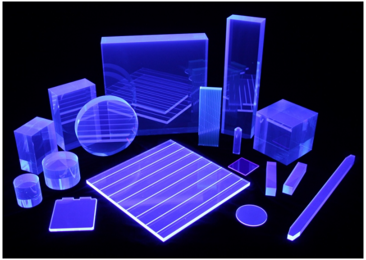
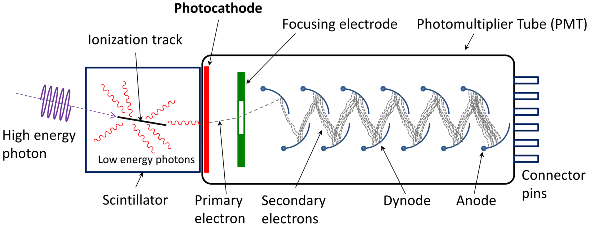
Scintillators & Photo Multipliers (PM)

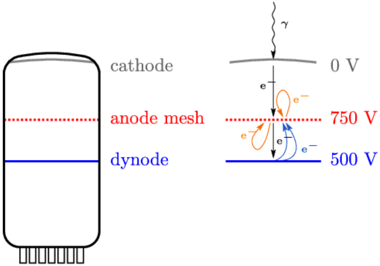
- Exist in different shape and forms and compositions (organic inorganic etc).
- Make use of the complex electronic structure of organic compounds to convert energy transferred to the medium to detectable photons.
- Often coupled to light guide/wavelength shifter (like this cool looking adiabatic light guide) to collect photons on detector downstream.
- Fast time response and usually cheap.
- Versatile but brutally complicated in the real details of operation.



Scintillators & Photo Multipliers (PM)

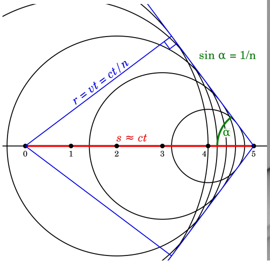
- Convert signal from a photon to many electrons
- Electron amplification chain
- Different structures the the PM itself but always same principle
- Might be sensitive to high magnetic field
- Can be solved using different geometries

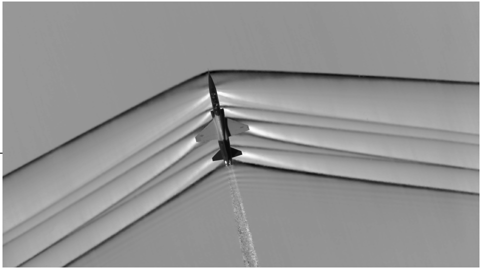




Cherenkov Radiation

If $v > c$ in the medium, an "EM shockwave", similar to a sound barrier shockwave, is created and known as Cherenkov Radiation.[3]



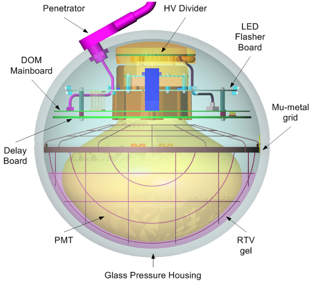


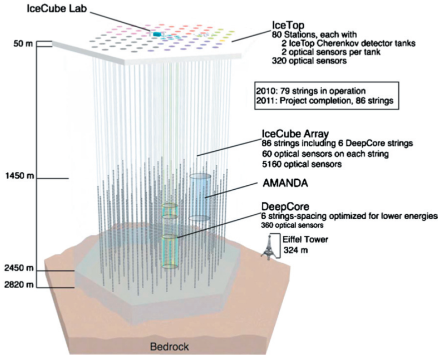
https://youtu.be/sve4qSlH3GE

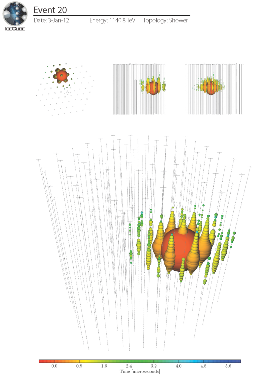
[3]See J.D. Jackson, Classical Electrodynamics, 3rd edition, (John Wiley and Sons, New York, 1998). for full demonstration

More information on the imaging technique for the plane https://www.nasa.gov/centers/armstrong/features/supersonic-shockwave-interaction.html

Cherenkov Radiation: ICE^3



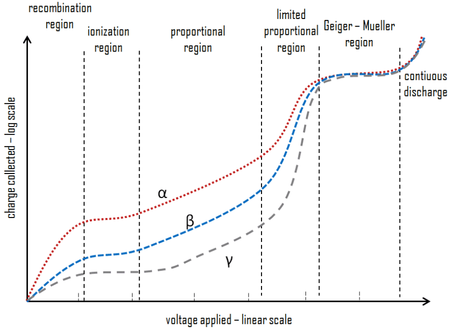


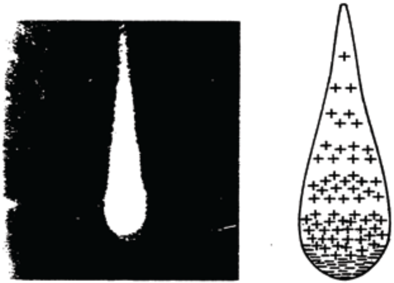


Detector making use of both the earth as a shielding material and south pole ice as its detection medium

Gaseous detectors

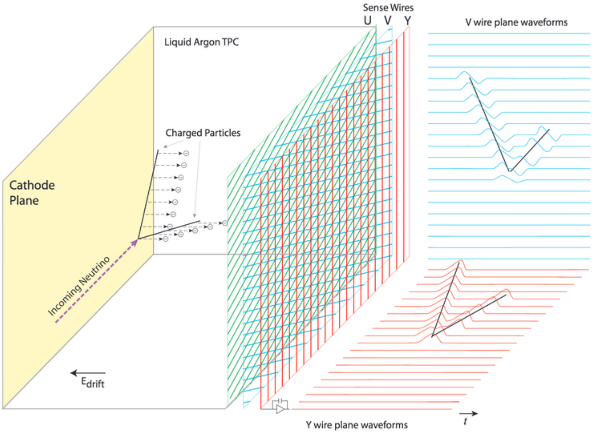
- If a potential difference is applied in the gas, charges will move (electron/ion)
- If field is high enough, an electron can kick others electrons off
- Those electrons can kick other electrons off...

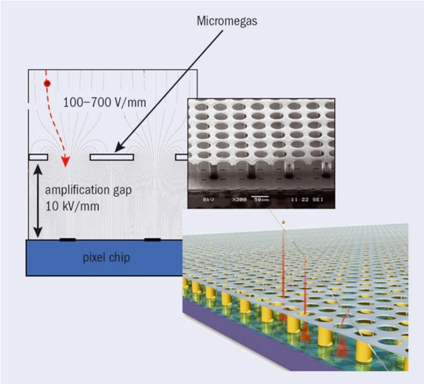




Gaseous detectors

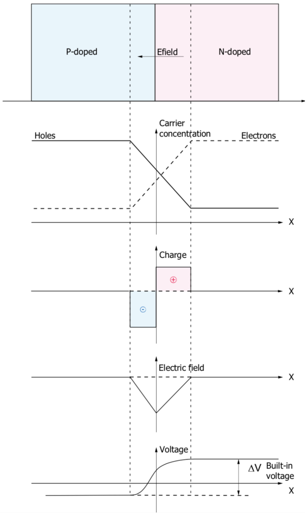
- ➢ Time Projection Chambers (TPC)
- ➢ Micro Pattern Gaseous Detectors (MPGD)





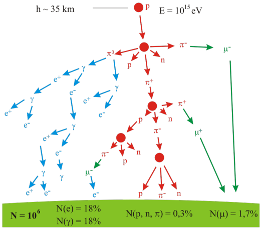
Semi-Conductors

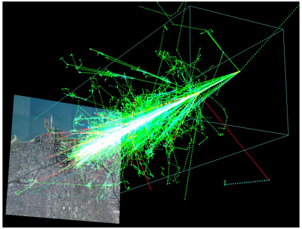
- Two pieces of semi-conductors are put in contact
- Each of the pieces are doped in different way, either as hole donor or electron donor
- The charges move to counter balance the deficit causing a depleted area with a field
- Biasing the semi-conductor further increases the depleted area
- If a particle passes through it will produce e^{-} hole pairs that will drift



Funny application: Use your phone as a particle detector

- ➢ Be part of a large particle detector array https://crayfis.io/[4]
- ➢ Turn your phone into a Radiation detector http://www.hotray-info.de/html/radioactivity.html[5]





[4] https://arxiv.org/pdf/1410.2895.pdf This being said I would do it with a busted phone rather than a new one, it uses the phone extensively...

[5] The video is hilarious, watch until the end https://youtu.be/qJcOq5sLxPo

Conclusions

We saw today that

- There are a lot of different types of detectors
- All detection principles relies on basic principles
- It is not because something is basic that it is easy
- It is all about moving charges

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