Electronics in a (large) physics experiment
Examples of big picture and small detail issues
Overview and goal

Recall that we started by talking about cascading stages. Almost all experiments have the same basic stages:

I’ll go through an example to see the details as well as some of the larger “systems” issues, which are typically where a physicist mindset is useful.
The “Rutherford Experiment” of Geiger & Marsden
Intro to the fixel project
The beams of protons are focused to 20 µm and passed through each other every 25 nanoseconds corresponding to a “luminosity” of $10^{34}$ protons/cm$^2$/s.
Detectors surround collision points
Rutherford-like scattering

$p\rightarrow 7\text{ TeV}$

Lead block (for shielding)

Scintillation screen

Slits

Alpha source

Alpha beam

Gold foil

The alpha particle

Rutherford's model of atom
Rutherford-like scattering

Would see an excess of scatters with momentum highly transverse to the beam direction.
To do this, we need to detect the produced particles & measure their 4-momentum. So surround collision point with sensors immersed in a solenoidal magnetic field so curvature of their path measures their momentum ($p_T$).
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Tracking particles requires:

- Detecting and recording their interaction with matter
- Pattern recognition to isolate a given particle’s “hits”
- Fitting that path to determine momentum
A sensor that we often use is a reverse biased diode.

Basic operation is similar to a photodiode.

A pn diode has a natural depletion zone free of charge carriers.
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Small leakage current from thermally generated e-hole pairs.

Photons generate charge carriers $\Rightarrow$ current.
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Small leakage current from thermally generated e-hole pairs.

Photons generate charge carriers \( \Rightarrow \) current.

Charged particle ionization generates charge carriers \( \Rightarrow \) current.

\( \approx 20k \) electrons in \( \approx 20\text{ns} \) for 300 \( \mu \text{m} \) thickness. \( \Rightarrow \) Electronics challenge.
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Signal amplification only in electronics.
⇒ Low noise amplifiers.

Signal is a pulse of current.
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Signal is a pulse of current.  
Current integrator gives total charge.
Making the sensors

Possible to get $O(1000)$ electron equivalent noise.
OK for 20k electron signal (300 µm).
Silicon structures normally $O(1)$ µm thick.
Need $O(100)$ V to deplete $\Rightarrow$ high purity, high resistivity.
Using $\approx$ full sensor sensitive to even small defect rate.
Mechanically mounting the sensors

- HPK Silicon Sensors
- Carbon Fiber Frame
- HV Kapton
- Pitch Adaptor
- Readout Hybrid
Position Resolution

Depends on size of diode…
Position Resolution

Depends on size of diode…
Lithography allows small diodes.

Charge weighting allows more precise position determination

\[ \bar{x} = \frac{\sum x_i q_i}{\sum q_i} \]
Position Resolution

Depends on size of diode. Lithography allows small diodes. Charge weighting allows more precise position determination.

\[ \sigma_x \approx \text{pitch}/\sqrt{12} \text{ if one channel} \]
\[ \sigma_x \approx \text{pitch}/4 \text{ if two channels} \]
\[ \sigma_x \approx \text{pitch}/2 \text{ if three channels} \]

Make the pitch small.
Typical pitch = 50 to 200 µm.
⇒ Many channels.
Many channel challenge

Build resistors into silicon.
Many channel challenge

Build capacitors into silicon.
Many channel challenge

ICs for 128 channels
Many channel challenge

Make a lot of connections
Many channel challenge

Make a lot of connections
Many channel challenge

Make a lot of connections
Many channel challenge

Kulicke and Soffa 8090 wirebonding machines
Many channel challenge

Also use microbonding on output of ASIC.
Many channel challenge
Also use microbonding on output of ASIC. Can be *encapsulated* once tested.
Resolution for pitch of 50 µm

\[ \sigma_x \approx 15 \, \mu m \text{ if one channel} \]
\[ \sigma_x \approx 10 \, \mu m \text{ if two channels} \]
\[ \sigma_x > 20 \, \mu m \text{ if three channels} \]
Global view
Global view
Arrange these in concentric cylinders to get full coverage
3D measurements

So far, only 2D ($r\phi$). Can get 3D measurements by:

- Detector length / $\sqrt{12}$
- Charge division
- Use sets of orthogonal detectors
- Use sets of stereo detectors

An “axial” silicon module for CMS
3D measurements

So far, only 2D (rφ). Can get 3D measurements by:

Detector length / sqrt(12)
Use sets of orthogonal detectors
Use sets of stereo detectors

A “stereo” silicon module for CMS
3D measurements

Two measurements in the same sensor.
3D measurements

Two measurements in the same sensor. O(1) degree stereo angle gives O(1) mm resolution for O(10) μm hit resolution.

Larger angle gives smaller resolution but more combinatorics…
Time dependence of signal

Next collision comes in 25 ns. Need some pulse shaping.
Pulse shaping of signal
Pulse shaping of signal
Pulse shaping of signal

Shaping the signal means we don’t have to reset the integrator capacitor after every measurement. Instead reset it “occasionally” during beam gaps that are orchestrated to come every $\mu s$ or so.
Reading out measurements

The amplifiers are relatively small

A set of hold capacitors; where each collisions’ charge measurement is held for later processing
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Then we need to “digitize the data”, i.e., convert the measured charge to number of electrons sensed that can be later processed by programs. This is ~ a multi-threshold comparator.
Reading out measurements

Convert the stored charge into binary information with an “Analog-to-Digital converter” (see Phys127B).

An approximate view is a comparator with several, switched, thresholds.
Reading out measurements

Transmit the binary information either with LVDS or optically on fibers.
Reading out measurements

Transmit the binary information either with LVDS or optically on fibers.

could make this variable to control amount of light, and minimize power consumption.
How do you calibrate the whole chain?

Inject a known amount of charge into the input. Can send command bits to adjust it.
How do you keep it from blowing up?

There is a whole set of monitoring and control circuits and systems.

Basic principle is

“Redundantly measure temperature, cooling flow & pressure, power supply voltages, etc., and interlock operation”.
Another, simpler example

Scintillation light
Another, simpler example

Scintillation light
Detect with a photo-diode operating in “avalanche” mode.

~30V
Another, simpler example

Scintillation light
Detect with a photo-diode operating in “avalanche” mode.
Cockroft-Walton supplies 28V bias to SiPMs

0.75x0.75x18" EJ-200 scintillator

3x3 mm optical coupling gel

3x3 mm SiPM mounted in reflector housing

Amp discriminator board

8 channel readout board, interfaces to Raspberry Pi which runs DAQ and provides 5V power from USB connection

Arrays of 8 channel boards form a hodoscope with flexible geometry
Amp discriminator board

3x3 mm SiPM mounted in reflector housing

3x3 mm optical coupling gel

8 channel readout board, interfaces to Raspberry Pi which runs DAQ and provides 5V power from USB connection

Cockroft-Walton supplies 28V bias to SiPMs

Arrays of 8 channel boards form a hodoscope with flexible geometry.
A small tracker with four rows of scintillator fibers, with a discriminator and 1-shot driving LEDs.
Another example; using an array of 2x2 mm scintillating fibers with SiPM readout.
Undergraduate research opportunities

Undergraduates can contribute to R&D, construction, testing, and operation of experiments even without having fully understood the physics goals.

You can contribute to the how without understanding the why.

Iff you have useful lab skills such as
- basic electronics
- debugging (handy with a scope and calmly methodical)
- acquire and analyze data to test performance
- programming

Doing this gets you deeply into a project where you can start to contribute, and then learn the why.
For example:
- Make that old oscilloscope work for this project
- Assemble and test this circuit board.

- Write a program to control this power supply, or function generator, or oscilloscope, or temperature sensor, …
- Take this incoherent pile of data and test whether X depends on Y.
- …
Surface Mount Soldering
Vacuum pickups
Circuit simulation with spice
Low noise measurements: Lock-in amplifier

Putting together the frequency, timing, and repeating is very powerful. That is the idea of a Lock-In Amplifier.

E.g., suppose you wanted to measure the brightness of a dim LED on a bright day. The sun is a noise source that you can’t reduce. But it is random.

Repeatedly pulse the LED at a known frequency & phase (time) to average away noise. But, need to filter out only that specific frequency.

This is modulate-demodulate, a la AM radio.

\[ A \sin(\omega_1 t)\sin(\omega_2 t + \phi) = \frac{A}{2} \left[ \cos[(\omega_1 - \omega_2)t - \phi] - \cos[(\omega_1 + \omega_2)t + \phi] \right] \]

Tune the pulsing and measurement frequency to be equal: \( \omega_1 = \omega_2 \)

so the cosine in the first term vanishes, and the second term can be removed with a low-pass filter. Then

\[ A \sin(\omega_1 t)\sin(\omega_2 t + \phi) = \frac{A}{2} \cos \phi \]

Adjust the phase to zero, and you get a measurement of the constant amplitude.
Low noise measurements: Lock-in amplifier

Putting together the frequency, timing, and repeating is very powerful.
That is the idea of a Lock-In Amplifier.
You can do this with a DC source by “chopping it”.

![Diagram of Lock-In Amplifier](image-url)
Low noise measurements: Lock-in amplifier

We can easily make a modulator if the signals are square waves.

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Low noise measurements: Lock-in amplifier

We can easily make a modulator if the signals are square waves.

Noise is random, signal is alternating. So invert the low parts and average. That keeps signal (amplitude) but cancels noise.
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This can precisely measure any DC value, or any AC signal’s V(t) if the modulator is much higher frequency than the signal’s frequency.