The Drift Chamber,
D. Peterson

Topics
- Physical description: container, wires, cell, gas, electric field, magnetic field
- Track momentum measurement: measurement error, scattering error
- Measurements with stereo wires
- Basic signal generation: ionization, electric field, drift, gasses, avalanche
- Observable signal: electron motion, ion motion, Sauli, amplifiers, discriminator basics, time measurement basics, resolution limit in the inner third (at the wire)
- Ion statistics, noise, amplification, discriminator threshold,
advanced and/or tangential topics

I am not going to talk about…

other topics in signal generation/measurement
  secondary ionization,
  diffusion,
  charge division,
Lorentz angle
other limits on the resolution
  calibration,
  construction techniques,
  alignment,
  electric field asymmetry,
  cell distortion in the magnetic field,
  wire sag, creep, electromechanical instability
bunch finding and coordination with the trigger
alternative chamber designs
  jet chambers,
  with and without multi-hit electronics (CDF vs BES)
straw tube chambers
A “drift chamber” is an adaptation of a “multi-wire proportional chamber” in which the fast timing information is measured to derive precision position information.

In CLEO, we measure the momentum vector \((x,y,z)\) of “all” charged particles in an event.
\[ R^2 = (R-s)^2 + \frac{L^2}{4} \]
\[ R^2 - 2Rs + s^2 + \frac{L^2}{4} \]

\[ s = \frac{L^2}{8R} \]

at 1 GeV, \( P_t = 150 \text{MeV} \times (2 \text{ R/meter}) \)

\[ \frac{1}{2R} = \frac{150 \text{MeV}}{P_t \text{/meter}} \]

\[ s = \frac{L^2}{4} \times \frac{150 \text{MeV}}{P_t \text{/meter}} \]

\[ \frac{\delta P_t}{P_t} = -\frac{\delta s}{s} \]

\( \text{mult scat : } \theta = 13.6 \text{MeV/} \beta c P (x/X_0)^{1/2} \)

\[ \delta s \sim \theta \text{, so } \frac{\delta P_t}{P_t} = \text{const}/(P_t s) = \text{const}_2 \]

measurement error:
\( \delta s \) is a constant; \( s^{-1} \) is proportional to \( P_t \)
so \( \frac{\delta P_t}{P_t} \) is proportional to \( P_t \)

and it is proportional to \( \varepsilon \), the single measurement error
Stereo measurements

The electronics read-out looks like a 2-dimensional measurement. The CLEO chambers use stereo wires to measure the z coordinate. The event displays show you the wire position at z=0.
Basic Chamber Construction

CLEO III/c  drift chamber  
1999 – present  

CLEO c  inner drift chamber  
2003 – present  
Design/Construction: 2001 - 2003
Inside the chambers ( DR2 )

Wires:
field wires, .0043 inch aluminum
110 μm
sense wires, .0008 inch tungsten
20 μm
Inside DR3

9796 sense wires
29693 field wires (about 3:1)

“wedding cake” structure
  individual rings and bands
1696 sense wires

conical “big” end plate
8100 sense wires

outer cathode
Inside the ZD

300 cells
about 1000 field wires

uses the same wires pins
and bushings as DR3

all stereo
this chamber was made to provide
sufficient z measurements
at small radius

the stereo angle is very large,
dϕ/dz = .1

The light patterns show the stereo angle.
The Cell (visually)

insulating bushings, showing the cell design
The Cell (schematic)

This is a 3:1 square cell. Although there are 8 field wires surrounding each sense wire, the pattern can be built from a basic block with 3 field wires and 1 sense.

DR3 half cell size: 7mm

The ZD uses a variation of this wire pattern, 3:1 hex, achieved by shifting the field wire layers by ¼ cell.

CLEO studies in 1994 showed that this modification did not change the response.

Note: wires are shown 21 times actual relative (DR3) size.
In DR3, the layers are arranged in super layers, with 4 layers/superlayer. Within the superlayer, there are the same number of wires per layer, half cell stagger.

To save space at superlayer boundaries,
the first field wire layer of the larger radius super layer
is also used as the last field wire layer of the smaller radius super layer.

The details won’t be discussed here.
The sense wire is a potential of 2100V (1900V) in the DR3 (ZD).
Field wires are at ground, for noise suppression.

Field lines are twisted in a magnetic field. This leads to many design considerations and corrections that will not be discussed.
Primary ionization: first step of the signal

A track goes through the gas and ionizes some of the molecules. How many? Bethe-Bloch isn’t very useful.

dE/dx=.307 (MeV/(g/cm²)) Z/A ρ 1/β² z² (ln(2mc²β²γ²/I) – β²)

It gives the total energy loss; we want the number of ion pairs.

There are measurements of the primary ionization cross section at min. ion.

<table>
<thead>
<tr>
<th></th>
<th>σ_p (10⁻²⁰ cm²)</th>
<th>λ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>18.6</td>
<td>1/3</td>
</tr>
<tr>
<td>Ar</td>
<td>90.3</td>
<td>1/24</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>161</td>
<td>1/43</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>269</td>
<td>1/72</td>
</tr>
</tbody>
</table>

where λ is the interaction length:

λ=22.4cm³/(6.023x10²³ σ_p)

In 1.4 cm of He-prop 60:40, ~43 prim. ions

note: wires are shown 7 times actual relative (DR3) size
There is secondary ionization. This occurs when a product of the primary ionization has energy greater than the ionization energy. However, this does not change the discreteness of the primary ion distribution.

The electrons drift to the anode. They follow the field lines. Drift velocity is on the next slide.

Diffusion disrupts the drift. Re-combination, or attachment to oxygen, could destroy the electrons.

7mm in DR3; 5mm in ZD

note: wires are shown 7 times actual relative (DR3) size
Drift velocity depends on acceleration in the electric field mean free path.

Drift velocity for Ar-methane mixtures

CLEO operates at 3 kV/cm (average)

note: velocity is saturated

also note:
those dashed lines
at a vertical value of 5 cm/µs
are all on top of each other

5 cm/µs = 50 µm/ns
I am amazed that the drift mechanism is accurate enough to provide 85 μm resolution. But it does.

Electrons in the low field region will either recombine, drift in much later, find their way to another sense wire. The positive ions do relatively little. The mass is 2000+ times that of the electrons.

7mm in DR3; 5mm in ZD

note: wires are shown 7 times actual relative (DR3) size
Radius of Avalanche

\[ E = \frac{Q}{r} \quad \text{where “Q” is } \lambda/(2\pi\varepsilon_0); \]

\[ \text{and } \lambda \text{ is the charge density} \]

Integrate…

\[ V = Q \ln(b/a) \]

where \( b \) is the cell “radius”

\[ a \text{ is the wire radius} \]

\[ V \text{ is the applied voltage} \]

\[ E = \frac{(V/r)}{(\ln(b/a))} \]

DR3, \( b=7000\mu m, a=10\mu m \)

\[ 1/\ln(b/a)=0.15 \]

\[ V/a=2100V / 10\mu m \]

At the wire surface: \( E = 31.5 \times 10^4 \) V/cm

and at \( r=63mm \): \( E = 5 \times 10^4 \) V/cm

This significance is described on the next slide.
Onset of avalanche

wire radius: 10µm

63 µm

22.4 \times 10^3 \text{ cm}^3 \quad \text{mole volume} \\
/ 6.023 \times 10^{23} \quad \text{atoms per mole} \\
/ (\sim 10^{-8} \text{ cm})^2 \quad \text{atom cross section} \ast \\
= 4 \mu\text{m} \quad \text{collision length}

the field strength (previous page)

at 63 mm radius

5 \times 10^4 \text{ V/cm or } 5 \text{ V/µm}

The energy at the collision length is

5 \text{ V/µm} \times 4\mu\text{m} = 20 \text{ V}

Average energy to create one ionization electron

<table>
<thead>
<tr>
<th>Gas</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>16</td>
</tr>
<tr>
<td>He</td>
<td>25</td>
</tr>
<tr>
<td>methane</td>
<td>13</td>
</tr>
<tr>
<td>ethane</td>
<td>12</td>
</tr>
<tr>
<td>propane</td>
<td>??</td>
</tr>
</tbody>
</table>

(Blum and Rolandi, p 6)

Why are field wires bigger than sense wires?

\ast \quad \text{This is very “hand-waving”.} \\
\text{I am using the order-of-magnitude size of an atom.} \\
\text{Of course, the hydro-carbon atoms are even bigger.}
The avalanche

Multiplication continues with a 4 \( \mu \text{m} \) length. When the electron cloud reaches the wire, we see a pulse.
Residuals: time-measured hit position are compared to the fitted position.

Parameterized as double gaussian with fixed 80% fraction in narrow component.

Narrow component: (average over entire cell) \( \sigma = 88 \, \mu m \)

Wide component: 200 \( \mu m \)
Average, full cell, all hits: 110 \( \mu m \)

( CLEO-III TDR Goal: 150 \( \mu m \) )
Resolution at the wire

Core $\sigma$ vs. drift dist, summed over layers (Bhabha, Run 114469)

Drift distance core resolution ($\mu$m)

<table>
<thead>
<tr>
<th>200</th>
<th>150</th>
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<tbody>
<tr>
<td>100</td>
<td>50</td>
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</tbody>
</table>

Drift distance (mm)

-8  -4  0  4  8

7mm in DR3; 5mm in ZD

Note: wires are shown 7 times actual relative (DR3) size
Ion spacing is a contribution to the resolution at low drift distance. The drift distance for the first electron is 0 to 210 µm adding a contribution of 60 µm to σ. What would happen if the discriminator threshold is equivalent to 3 primary electrons? At zero impact, the drift distance for the 3rd electron would be \{420 – 630\} µm. At 500 µm impact, the drift distance for the 3rd electron would be \{652 – 804\} µm, i.e. increasing by only 200 µm.
The Signal

I introduced the pulse 4 slides back. How is this signal developed?
Understanding more about the signal will help in understanding the electronics design.

Note: we are making $\sigma=100\mu$m distance measurements.
The gas velocity is $28\mu$m/ns (He-propane 60:40).
Thus, the time measurement must have precision: $\sigma=3.5$ ns.
The resolution tells us that leading edge must be defined to 3.5 ns.

The signal shown has significant voltage over about 150ns.
(Note: the total drift time in our cell is 250ns.)
Some of the substructure is individual ions, some is electronic noise.
The signal and the lies (well, misunderstandings)

“almost all the energy and all the signal in a proportional counter are due to the motion of the positive ions.”

*Blum and Rolandi*, p155

“The signal is due to the motion of the positive ions” *various unnamed*

“it is an energy argument” *ibid*

“it says so in Sauli” *ibid*

The ions move about 10,000 times slower than the electrons.

Therefore, the time across the cell is ~2.5 ms and this is inconsistent with the observed signal.

One will never get 100μm resolution with the time dependence on the ion motion.

And, who is Sauli?
“The detected signal, negative on the anode and positive on the cathode, is a consequence of the change in energy of the system due to the movement of the charges.”

*Fabio Sauli*, CERN 77-09, p 44.

read on…

“ It is therefore normal practice to terminate the counter with a resistor such that the *signal is differentiated* with a time constant $\tau=RC.$”

*ibid*, p 46.

in CLEO, $C=330 \times 10^{-12} \text{ F}$

termination resistance =0
The truth about the signal.

“In the case where $R_2C_2$ and $R_2C_1$ are small compared to the pulse rise time,…

…the potential of the wire is re-established during the development of the pulse…

…the counter then acts as a current source…

…and the signal is the current that flows through $R_2$.

…and The current signal involves the derivative of (the energy time dependence).”

Blum and Rolandi, p156,157,158

Notice, they didn’t say anything about $R_1$; that is 1 MΩ but does not determine the time characteristics.

$R_2$ is the amplifier input impedance, which is $\approx 0$, so the condition holds.

KME will describe the amplifiers.
The circuit and noise

Noise can be injected at several places in the system.

Radiation noise can lead to real ionization which will amplified by the avalanche and the electronics amplifier.

The wire is a big antenna. RF noise can be amplified by the electronics amplifier.

Electronics noise can be on either side of the electronics amplifier.

We have several ways of changing the “threshold” to reject noise.
- change the HV
- change the electronics amplifier gain
- change the discriminator threshold.

The most effective method is to increase the HV and increase the discriminator threshold.

But, this could damage the chamber so we must find a balance.

Matt will describe the discriminators (TQT).
Time measurement, basics

We have used two types of timing devices in CLEO. The capacitor timing was used in CLEO I and II. It was designed in-house. There were many problems: non-linear response on the RC circuit, channel-to-channel variations that required another layer of calibration, and (most significant) the need for a pedestal reset during live time.

The clock timing circuits are used in CLEO III/c. This design solves the above issues. They are commercial. We bought the French ones, probably because we could not afford the Italian product. We gripe a lot, but we would not survive with the capacitor circuits.

Capacitor ramp-down timing

Clock timing

Matt will describe the TDCs
DR3 at the outer radius

- super layer 8
- ground strips
- crimp pin ends
- HV connections
- signal connections
- cathodes
- chamber support
- RICH gas (run!)
DR3 at medium radius

- super layer 1 3,4
- ground strips
- crimp pin ends
- HV connections
- signal connections
- axial HV distribution
- DR3 gas pipe
We will not see this again if we are lucky.

DR3 axial ring 1, layer 2 connected, this is west.

DR3 axial signal coax

DR3 ground strips

DR3 F1- voltage distribution

ZD cables

ZD gas

ZD support

beam pipe cooling

permanent magnet support ring

beverage
It’s FUN