TRACKING DETECTORS

OBJECTIVE: OBSERVE TRAJECTORY OF CHARGED PARTICLE WITH AS LITTLE INTERFERENCE AS POSSIBLE.

→ USE A "THIN" DETECTOR

SCINTILLATORS ($\sigma \sim$ cm)

GAS BASED DETECTORS ($\sigma \lesssim$ mm)

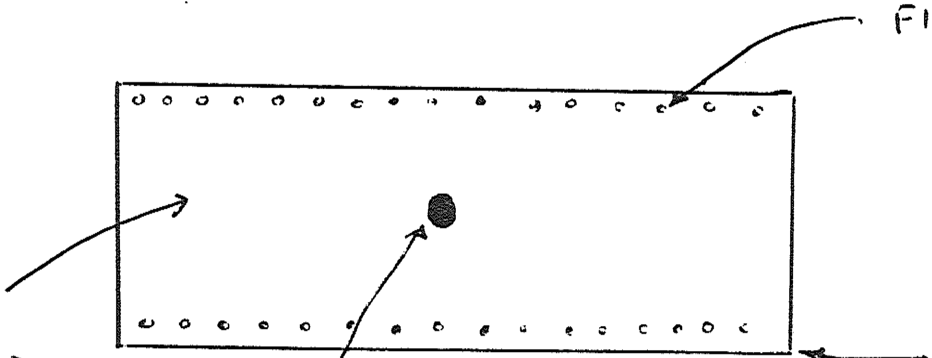
SILICON DETECTORS ($\sigma \simeq 10\,\mu m$)

START WITH GAS BASED DETECTORS:

- MULTI-WIRE PROPORTIONAL CHAMBER
- DRIFT CHAMBER
- TIME PROJECTION CHAMBER.

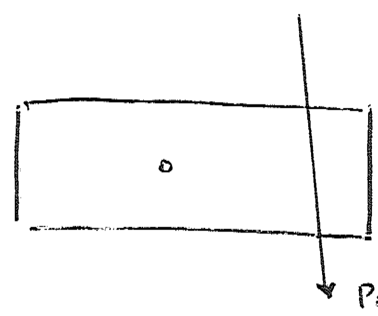
OFTEN USE COMBINATIONS OF CHAMBERS TO MEASURE DIFFERENT PROPERTIES OF A PARTICLE.

SCHEMATIC OF A WIRE CHAMBER



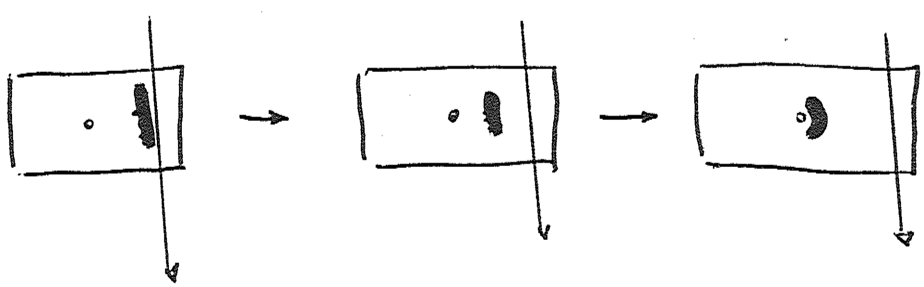
THREE ESSENTIAL STAGES

① IONISATION



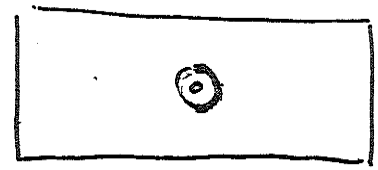
ELECTRONS FROM GAS ARE DISTURBED BY PASSAGE OF CHARGED PARTICLE (dE/dx!)

② DRIFT



IONISED ELECTRONS FORCED BY THE DRIFT FIELD TO MIGRATE TOWARDS THE ANODE WIRE. A "DIRECTED" RANDOM WALK.

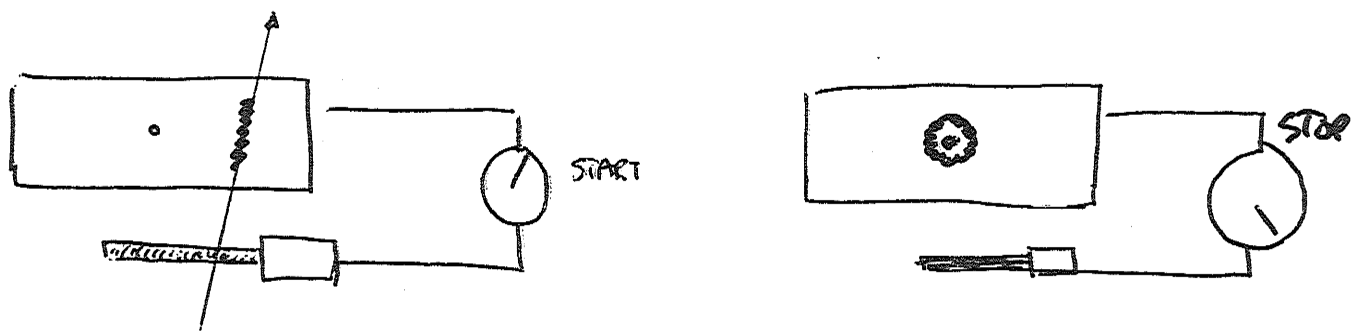
③ **AMPLIFICATION**



IN THE HIGH FIELD REGION NEAR THE ANODE WIRE THE IONISATION ELECTRONS GAIN ENOUGH ENERGY BETWEEN COLLISIONS TO THEMSELVES IONIZE.

THIS RESULTS IN AN AVALANCHE WITH GAINS UP TO 10^7 POSSIBLE.

DRIFT AND DIFFUSION OF ELECTRONS



DRIFT CHAMBER WORKS BY MEASURING THE TIME IT TAKES FOR ELECTRONS TO ARRIVE AT THE ANODE.

AS ELECTRONS DRIFT DIFFUSION CAUSES ORIGINALLY WELL DEFINED CLOUD TO SPREAD OUT ⇒ ARRIVES AT ANODE "FATTER" ⇒ LESS WELL DEFINED INTERPRETATION OF ORIGINAL POSITION

LIMIT ON RESOLUTION OF DETECTOR.

IONISATION TURNS 1 NEUTRAL ATOM

$\hookrightarrow$ 1 ELECTRON (SMALL MASS & SIZE)

1 POSITIVE ION (LARGE & HEAVY)

UNDER THE INFLUENCE OF DRIFT FIELD THEY MOVE AWAY FROM THEIR BIRTHPLACE. THIS IS A RANDOM WALK (MULTIPLE COLLISIONS) OR DIFFUSION

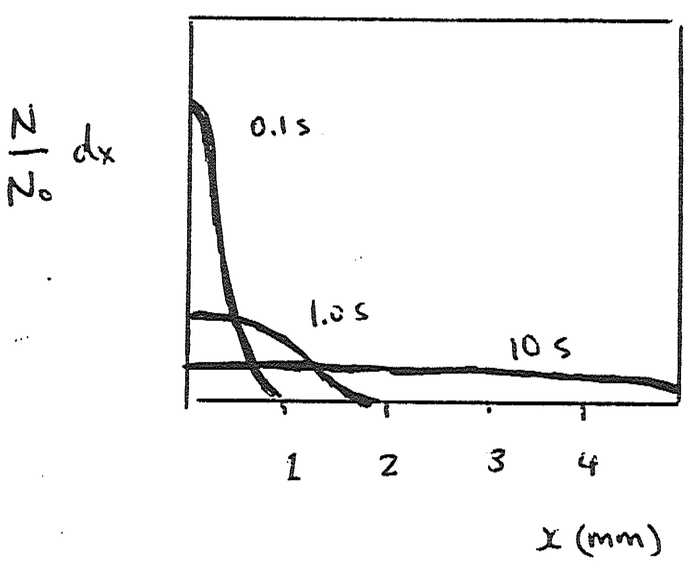
IN ABSENCE OF EXTERNAL FIELD THEY FOLLOW A TIME DEPENDENT GAUSSIAN SPATIAL DISTRIBUTION

$$\frac{dN}{N} = \frac{1}{4\pi Dt} e^{-(x^2/4Dt)} dx$$

$$\sigma^2 = 2Dt$$

D = Diffusion Coefficient

t = time



DIST'N OF IONS IN AIR

R.M.S. $= \sqrt{2}\sqrt{Dt}$ IN ANY DIREC

CHARACTERISTICS OF DIFFUSION

- MEAN FREE PATH BETWEEN COLLISIONS

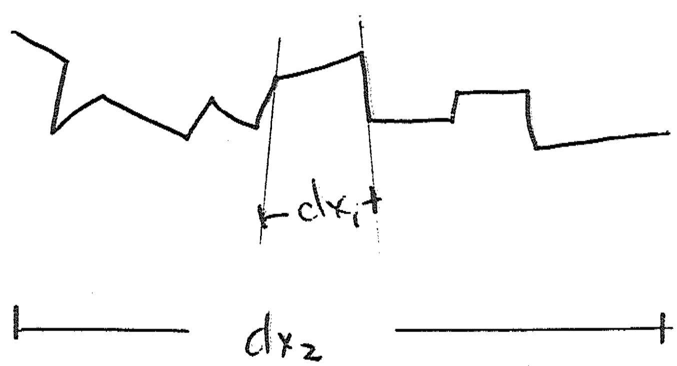
  IONS $\sim 10^{-5}$ cm ELECTRONS $\sim 10^{-6}$ cm

- AVERAGE VELOCITY BETWEEN COLLISIONS:

  $5 \times 10^{+4} - 2 \times 10^{5}$ cm/s (IONS)

  10^{7} cm/s (ELECTRONS)

IN PRESENCE OF AN ELECTRIC FIELD:



$\frac{dx_1}{dt}$ = THERMAL VELOCITY

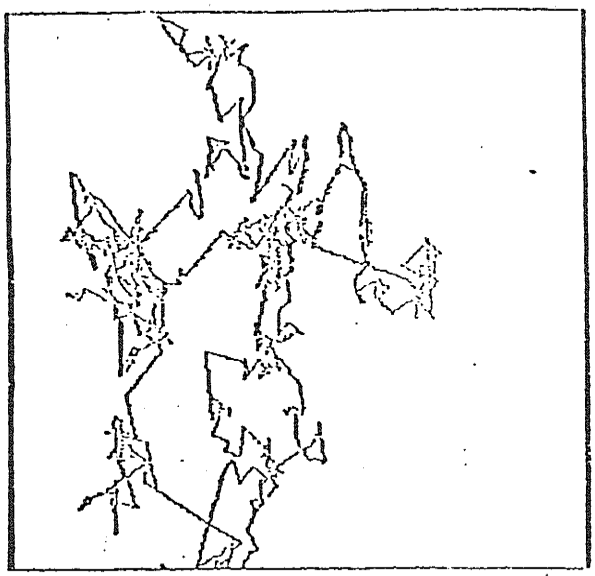
$W \equiv \frac{dx_2}{dt}$ = DRIFT VELOCITY

IONS DRIFT VELOCITY DEPENDS ON $|\vec{E}|/p$ TO VERY HIGH $|\vec{E}|$

$$W = \frac{\mu |\vec{E}|}{p}$$

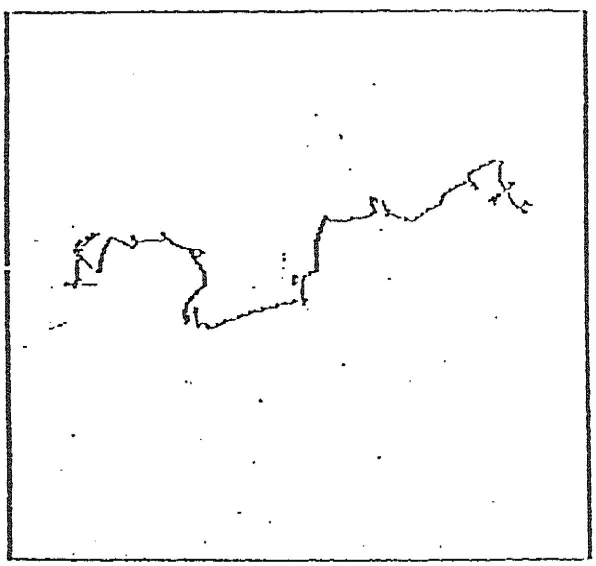
μ = MOBILITY SPECIFIC TO ION SPECIES AND SURROUNDING GAS

P = Pressure of Surrounding Gas.

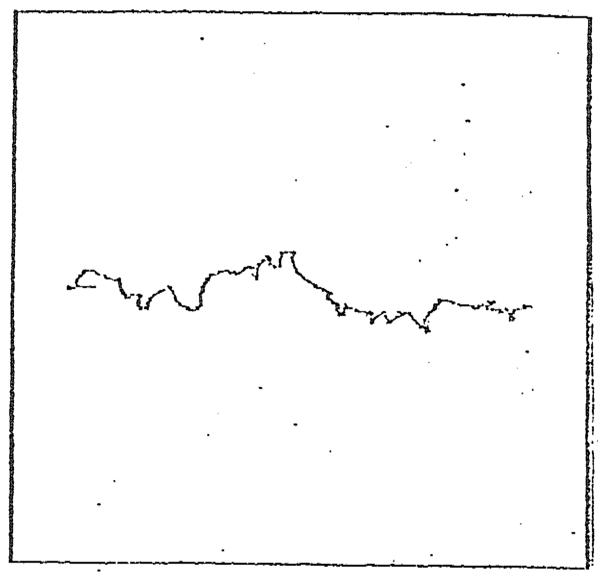


E/P=10

E/P=100



E/P=500

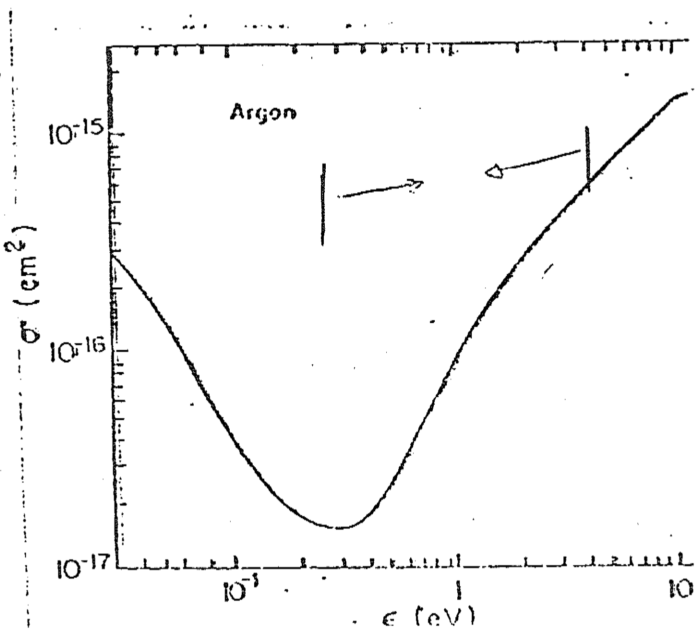


FIELD DIRECTION →

E/P=1500

ELECTRONS. MOBILITY IS NOT CONSTANT

MEAN FREE PATH DEPENDS ON ELECTRON INTERACTION CROSS-SECTION WHICH IN TURN DEPENDS ON ATOMIC LEVELS ETC.

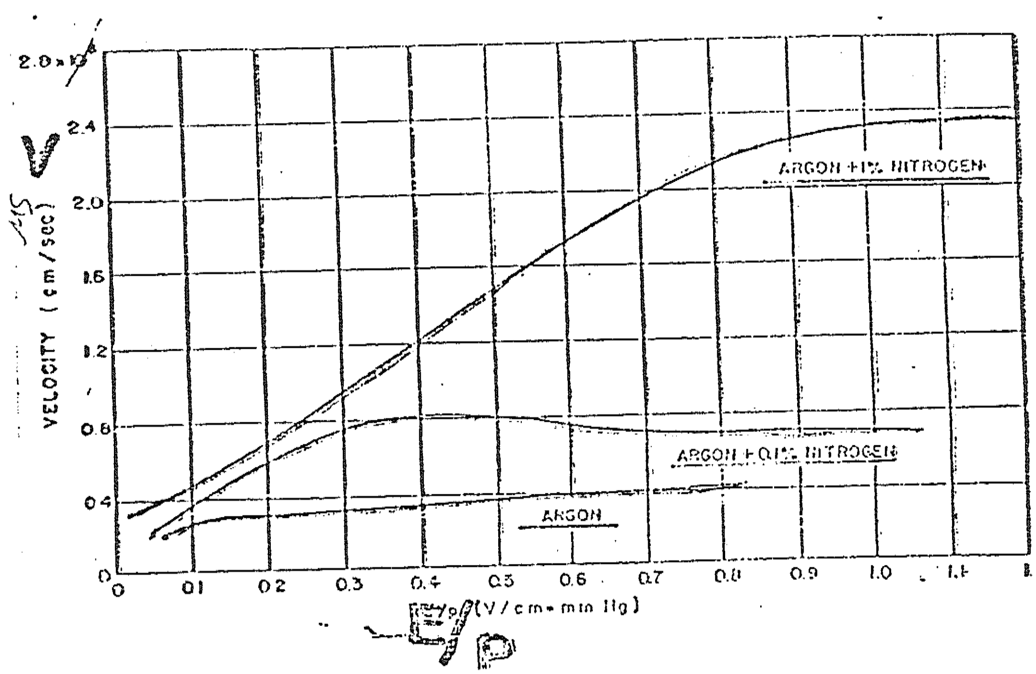


RAMSAUER CROSS-SECTION FOR ELECTRONS IN ARGON

LOW σ $\Rightarrow$ LONG MEAN FREE PATH

$\Rightarrow$ EXTRA DIFFUSION

THESE CROSS-SECTIONS ARE GAS DEPENDENT



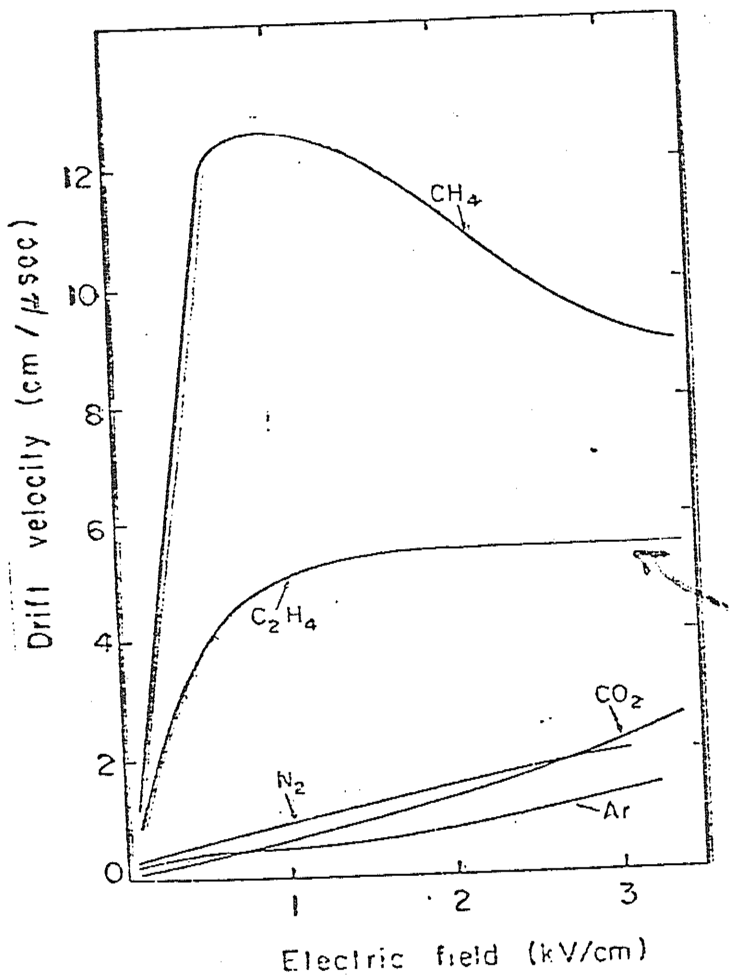
SMALL ADDITIONS $\Rightarrow$ BIG EFFECTS

6

SATURATED DRIFT VELOCITIES

AS $|\vec{E}|$ INCREASES SO DOES ELECTRON ENERGY

THIS CAN INCREASE INTERACTION CROSS-SECTION REDUCING THE MEAN FREE PATH AND HENCE DRIFT VELOCITY



THIS CAN LEAD TO A <u>SATURATION OF DRIFT VELOCITY</u>

IDEAL FOR DRIFT CHAMBERS WHERE YOU WANT A PRECISE d VS t RELATIONSHIP TO DETERMINE DRIFT DISTANCE

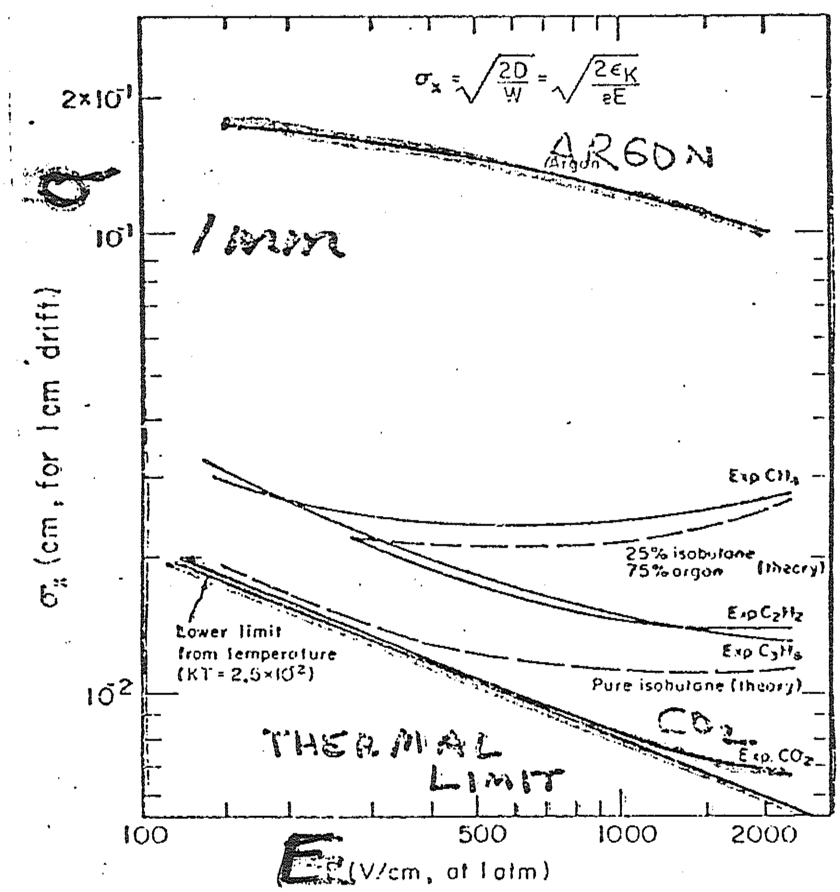
DIFFUSION LIMIT TO SPATIAL ACCURACY

RECALL $\sigma^2 = 2Dt$

DEFINE $\sigma(1\text{cm}) = \sqrt{\frac{2D}{W}}$ $\quad \because t = \frac{1\text{cm}}{W}$

NB $\sigma(x) = \sigma(1\text{cm})\sqrt{x}$

$\sigma(1\text{cm})$ is ANOTHER FIGURE OF MERIT FOR ACCURACY IN A DRIFT CHAMBER



NOTE THAT $\sigma(1\text{cm})$ DROPS SLIGHTLY FOR INCREASING $|\vec{E}|$

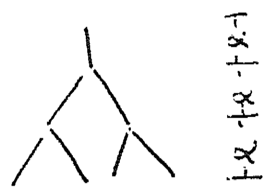
HIGHEST ACCURACY FOR "COOL GASES" LIKE CO_2 WHERE DIFFUSION SMALL

PRICE TO PAY IS DRIFT VELOCITY NOT SATURATED.

AMPLIFICATION (AVALANCHE THEORY)

AS $|\vec{E}|$ INCREASES ELECTRONS GAIN ENOUGH ENERGY TO, THEMSELVES, IONISE.

SIMPLE CASCADE MODEL
→ ASSUME UNIFORM $|\vec{E}|$
→ CONSTANT MEAN FREE PATH α

⇒ 

IF ELECTRONS IONISE IN $\sim \alpha$ THEN WE GET AN EXPONENTIAL CASCADE

$$dn = n\,\alpha\,dx$$

α = DOUBLING LENGTH OF CASCADE

$$\Rightarrow \quad n = n_0 e^{\alpha x}$$

NUMBER OF ELECTRON IN CASCADE

$$M = \frac{n}{n_0} = e^{\alpha x}$$

MULTIPLICATION FACTOR OR GAIN

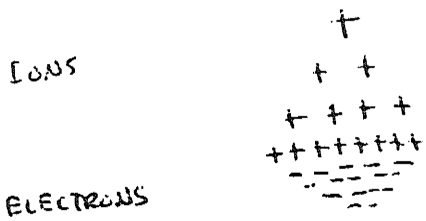
FOR NON-UNIFORM FIELDS (IE. AROUND A WIRE $|\vec{E}| \sim \frac{1}{r}$)

$$\alpha = \alpha(E) = \alpha(x)$$

$$M = \exp \int_{x_1}^{x_2} \alpha(x)\,dx$$

↳ TOWNSEND COEFFICIENT.

AVALANCHE SHAPE



POSITIVE IONS MOVE SLOWLY

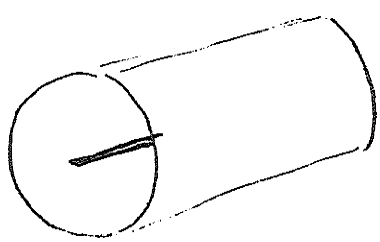
HALF WERE CREATED IN LAST MEAN FREE PATH

$\Rightarrow$ TEAR DROP SHAPE

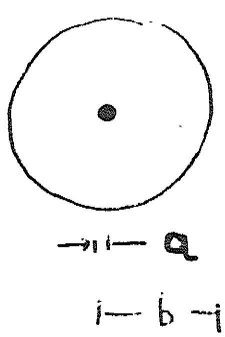
PROPORTIONAL CHAMBERS

- FOR "CORRECT" HV THE SIZE (INTEGRATED CHARGE) OF THE DETECTED PULSE IS PROPORTIONAL TO THE ENERGY DEPOSITED IN THE COUNTER

SIMPLEST EXAMPLE



THIN WIRE (ANODE) INSI[DE] A GROUNDED METAL CYLINDER (CATHODE).



FOR $a < r < b$

$$E = \frac{CV_0}{2\pi\epsilon_0} \frac{1}{r}$$

$$V = \frac{CV_0}{2\pi\epsilon_0} \ln\left(\frac{r}{a}\right)$$

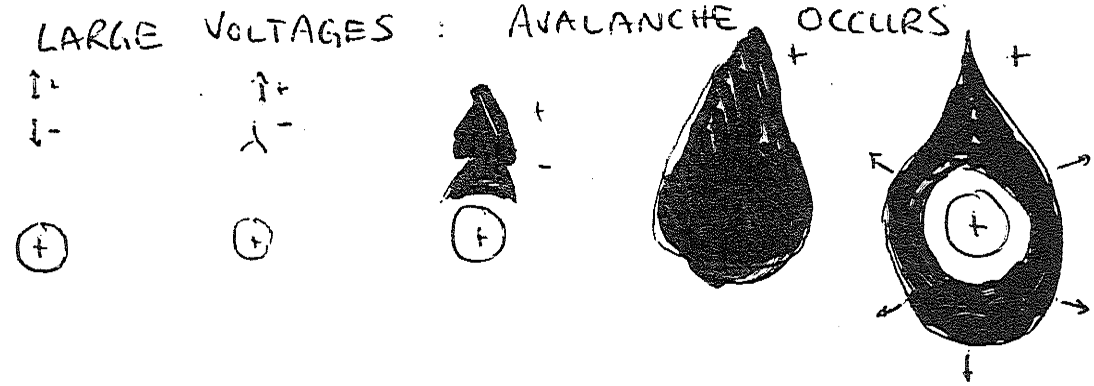
TYPICALLY $a \sim 10 - 50\ \mu m$

FOR LOW VOLTAGES : ENOUGH TO ATTRACT IONISED ELECTRONS TO WIRE BUT NOT ENOUGH FOR AMPLIFICATION

$$\text{SIGNAL} = V = \frac{q}{C} = \frac{ne}{C}$$

n = # of primary electrons

FOR LARGE VOLTAGES : AVALANCHE OCCURS



DIFFUSION CAUSES AVALANCHE TO SURROUND WIRE

ELECTRONS ARE COLLECTED WITHIN ~ 1 ns

POSITIVE IONS MIGRATE SLOWLY TOWARDS CATHODE

$$W = \frac{\mu E}{P}$$ $\Rightarrow$ ION VELOCITY FALLS AWAY FROM WIRE

SIMPLE ELECTROSTATICS

MOVING A CHARGE Q A DISTANCE dr IN A SYSTEM OF CAPACITANCE $C\ell$ ($C \equiv$ CAPACITANCE / UNIT LENGTH)

$\Rightarrow$ INDUCED SIGNAL $$dv = \frac{Q}{C\ell V_0} \frac{dV}{dr} dr.$$

V_0 = TOTAL VOLTAGE BETWEEN ANODE & CATHODE

$\frac{dV}{dr}$ = VOLTAGE GRADIENT (LOCALLY) aka. ELECTRIC FIELD.

CONSIDER SIGNAL FROM CHARGES PRODUCED WITHIN A DISTANCE λ OF THE WIRE. (ie $r = \lambda + a$)

ELECTRON CONTRIBUTION:

$$v^- = \frac{-Q}{\ell C V_0} \int_a^{a+\lambda} \frac{dV}{dr} dr = -\frac{Q}{2\pi\epsilon_0 \ell} \ln\left(\frac{a+\lambda}{a}\right)$$

POSITIVE ION CONTRIBUTION:

$$v^+ = \frac{Q}{\ell C V_0} \int_{a+\lambda}^{b} \frac{dV}{dr} dr = \frac{-Q}{2\pi\epsilon_0 \ell} \ln\left(\frac{b}{a+\lambda}\right)$$

TOTAL SIGNAL:

$$v = v^+ + v^- = \frac{-Q}{2\pi\epsilon_0 \ell}\left[\ln\left(\frac{a+\lambda}{a}\right) + \ln\left(\frac{b}{a+\lambda}\right)\right]$$

$$V^+ + V^- = \frac{-Q}{2\pi\epsilon_0 l} \ln\left(\frac{b}{a}\right) = \frac{Q}{lC}$$ OK

RATIO : $$\frac{V^-}{V^+} = \frac{\ln(a+\lambda) - \ln(a)}{\ln(b) - \ln(a+\lambda)} \simeq 1\%$$

$a = 10\,\mu m$
$\lambda = 1\,\mu m$
$b = 10\,mm$
(TYPICAL VALUES)

$\Rightarrow$ ELECTRON CONTRIBUTION TO SIGNAL $\simeq 0$.

TIME DEVELOPMENT OF SIGNAL

CONSIDER ONLY POSITIVE IONS.

$$v(t) = -\int_0^t V(t')\,dt' = \frac{-Q}{2\pi\epsilon_0 l} \ln\left(\frac{r(t)}{a}\right)$$

$t=0$ when ions at $r = a$.

$$\frac{dr}{dt} = w = \frac{\mu E}{P} = \frac{\mu}{P} \frac{CV_0}{2\pi\epsilon_0} \frac{1}{r}$$

$$\int_a^r r'\,dr' = \frac{\mu}{P} \frac{CV_0}{2\pi\epsilon_0} \int_0^t dt$$

$$\frac{r^2}{2} - \frac{a^2}{2} = \frac{\mu}{P} \frac{CV_0}{2\pi\epsilon_0} t$$

$$\Rightarrow \quad r(t) = \left(a^2 + \frac{\mu}{P} \frac{C V_0 t}{\pi \epsilon_0} \right)^{1/2}$$

$$\Rightarrow \quad V(t) = \frac{-Q}{4\pi\epsilon_0 l} \ln\left(1 + \frac{\mu C V_0 t}{\pi \epsilon_0 P a^2} \right)$$

$$\doteq \frac{-Q}{4\pi\epsilon_0 l} \ln\left(1 + t/t_0 \right) \qquad \mathrm{I}$$

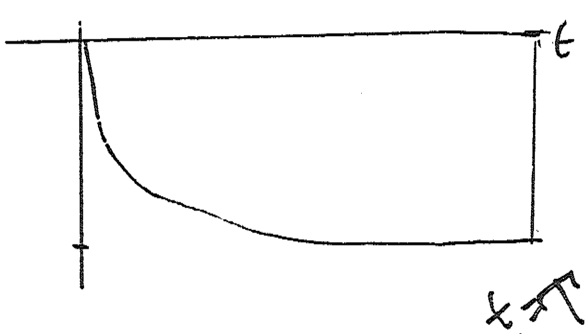
LET T BE THE TOTAL DRIFT TIME OF POSITIVE IONS (ie time to get from $r=a \rightarrow r=b$)

$$r(T) = b = \left(a^2 + \frac{\mu}{P} \frac{C V_0}{\pi \epsilon_0} T \right)^{1/2}$$

$$\mathrm{II} \qquad T = \frac{\pi \epsilon_0 P}{\mu C V_0} \left(b^2 - a^2 \right)$$

$a = 10\ \mu m$
$b = 8\ mm$
$C = 8\ pF/m$
$\mu = 1.7 \frac{cm^2}{s \cdot V \cdot ATM}$ (ARGON)
$V_0 = 3\ kV$

$$= 550\ \mu s.$$



THIS IS A VERY LONG TIME (EVEN IN SLOW EXPERIMENTS LIKE LEP)

CROSS-CHECK :

$$V_{max} = V(T)$$

$$= \frac{-Q}{4\pi\epsilon_0 l} \ln\left(1 + \frac{b^2 - a^2}{a^2}\right)$$

$$= \frac{-Q}{2\pi\epsilon_0 l} \ln\left(\frac{b}{a}\right) \quad \checkmark$$

WHAT ABOUT TIME TO GET

$$V = V_{max}/2$$

$$V(t_{1/2}) = \frac{V_{max}}{2} = \frac{-Q}{4\pi\epsilon_0 l} \ln\left(\frac{b}{a}\right) = \frac{-Q}{4\pi\epsilon_0 l} \ln\left(1 + \frac{t}{t_0}\right)$$

$$\Rightarrow \ln\left(1 + \frac{t_{1/2}}{t_0}\right) = \ln\left(\frac{b}{a}\right) \qquad t_{1/2} = t_0\left(\frac{b}{a} - 1\right)$$

$$= T \frac{a^2}{(b^2 - a^2)} \left(\frac{b-a}{a}\right)$$

From I & II $\quad t_0 = T\left(\frac{a^2}{b^2 - a^2}\right)$

$$\Rightarrow t_{1/2} = T \frac{a}{(a+b)}$$

$$a = 10\,\mu m \qquad b = 10\,mm$$

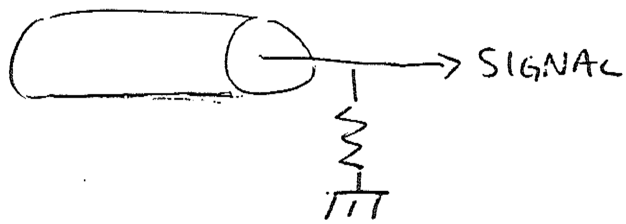
$$\Rightarrow t = T/1000$$

THUS GET $\frac{1}{2}$ THE SIGNAL IN $\frac{1}{1000}$th OF THE TIME

THIS IS MUCH MORE PRACTICAL.

LEADS TO A WHOLE ART OF POST-CHAMBER PULSE SHAPING

SIMPLEST REALISATION: RC - CIRCUIT



$C =$ INTRINSIC COAXi CAPACITANCE

$8\,pF/m \sim 1m$ bo

$\Rightarrow 8\,pF$

$R =$ TERMINATOR

$\simeq 1\,M\Omega$

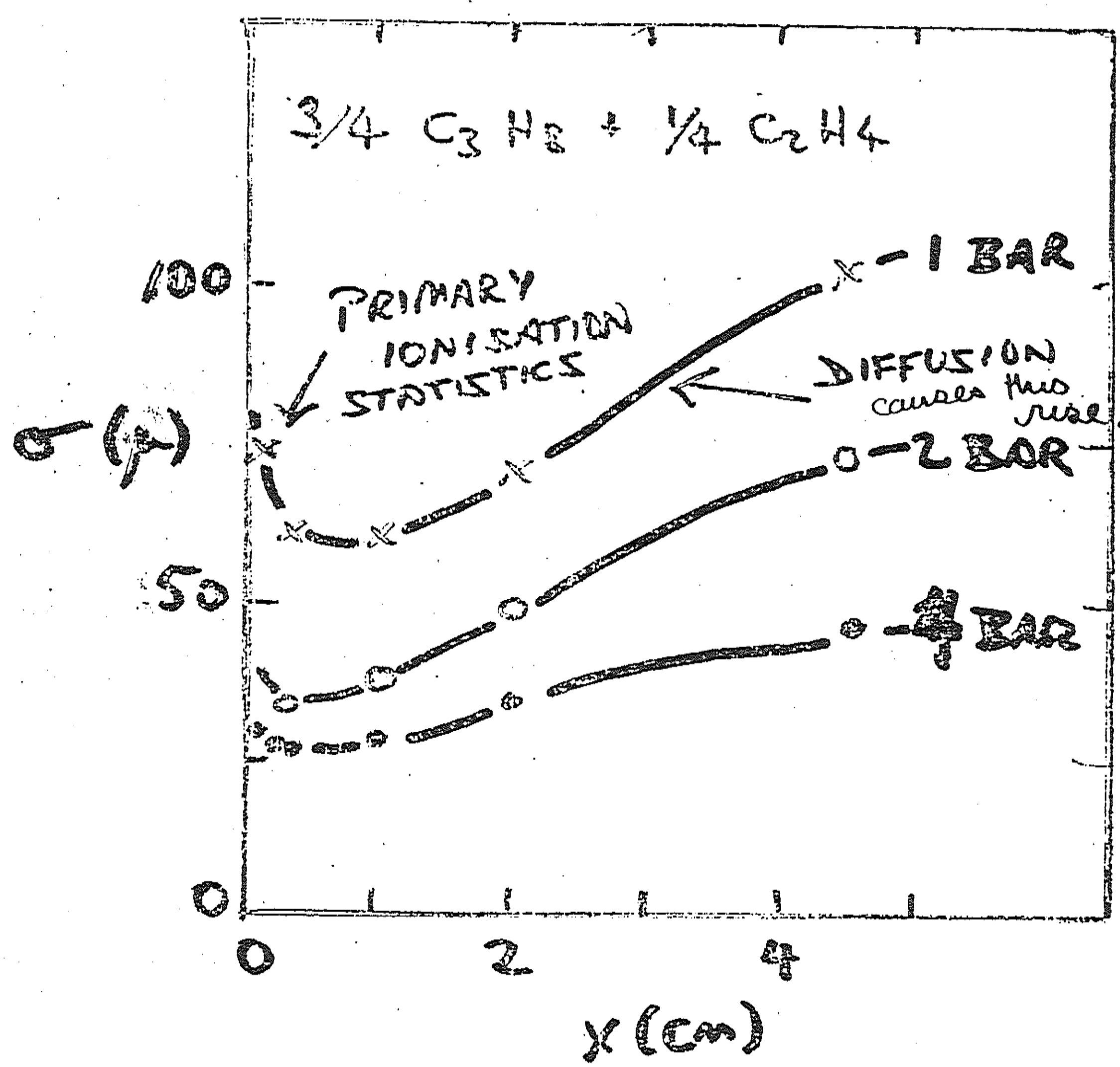
$\Rightarrow RC = 8\,\mu s.$

Oct. 21 SI

DRIFT CHAMBER RESOLUTION

vs.

GAS PRESSURE

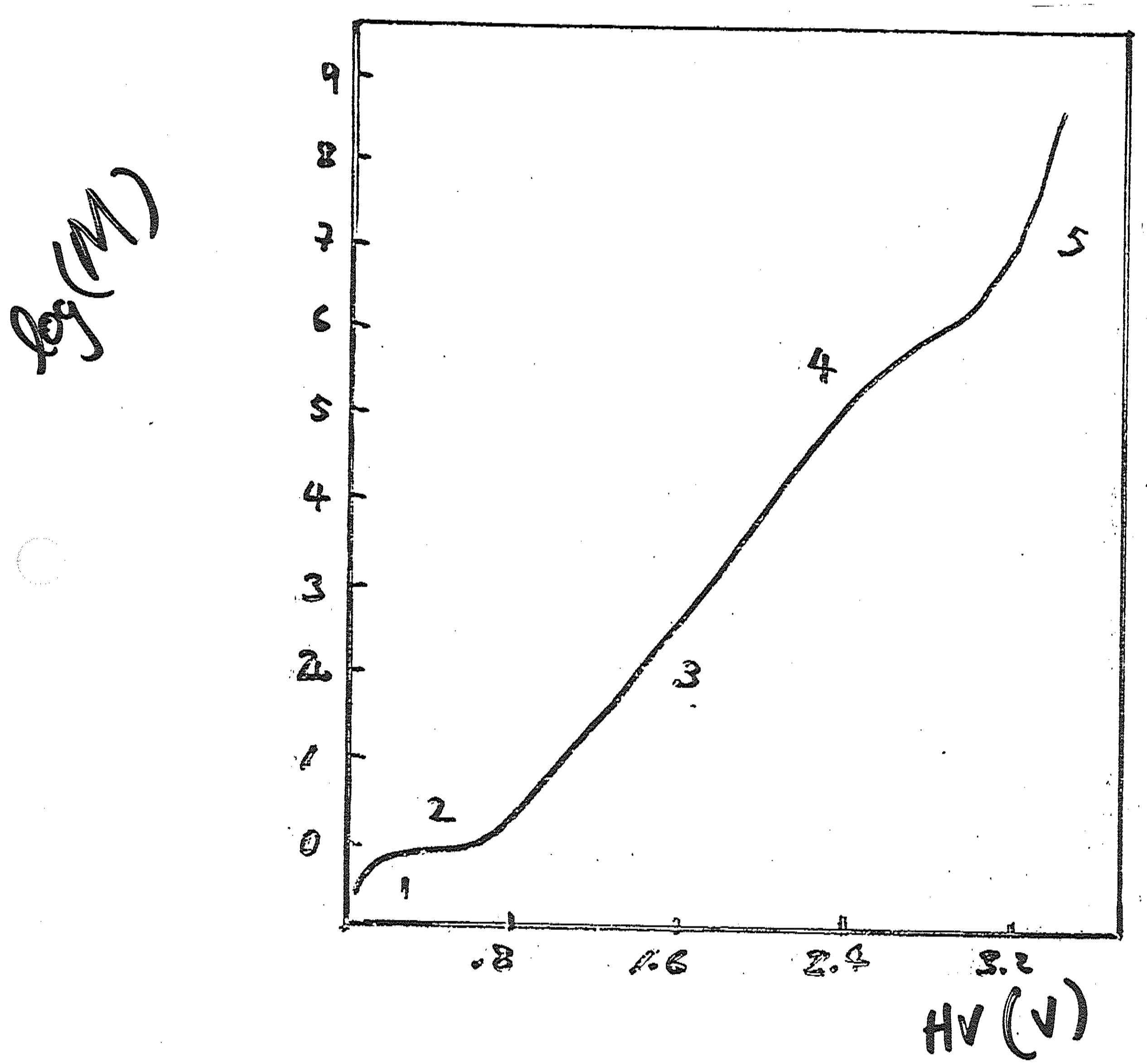


AT LOW PATH LENGTHS ACTUAL IONISATION "CLUMPS" (POISSON STATISTICS) WHICH CAN CAUSE RESOLUTION FLUCTUATIONS

Skip in 2024

TRACKING CHAMBERS (Continued)

CHAMBER GAIN OPERATING REGIONS



REGION 1 — NO AMPLIFICATION - SOME SIGNAL LOST DURING DRIFT!

REGION 2 — ION CHAMBER MODE - NO AMPLIFICATION, BUT ALL PRIMARY IONISATION COLLECTED.

REGION 3 - PROPORTIONAL MODE PULSE SIZE CORRELATED TO DEPOSITED CHARGE GAINS UP TO 10^4.

REGION 4 - LIMITED STREAMER MODE

GAIN TOO HIGH TO PRESERVE PROPORTIONALITY. POSITIVE ION CLOUD FROM CHARGES ARRIVING EARLY SCREEN THE ANODE, REDUCE ⇒ REDUCE GAIN FOR SUSEQUENT ARRIVALS

→ ADVANTAGE FASTER OPERATION WHERE SIGNAL PULSE HEIGHT NOT IMPORTANT. (OR SMALL GAP OPERATION

REGION 5 - GEIGER - MÜLLER MODE

→ AVALANCHE GENERATES PHOTONS
↳ LONG MEAN FREE PATH.

→ AVALANCHE SPREADS ALL ALONG ANODE
⇒ ENORMOUS PULSE

- CHAMBER IS DEAD FOR A LONG TIME.

- ADVANTAGE IS NO SOPHISTICATED READOUT ELECTRONICS IS NEEDED.

CHOICE OF GAS

- START WITH A NOBLE GAS
    - NOT ELECTRONEGATIVE (GOOD FOR DRIFTING)
    - LARGE TOWNSEND COEFFICIENT

- PICK ONE WITH HIGH SPECIFIC IONISATION
  ⇒ LOTS OF IONS / CM OF PARTICLE TRACK

- ARGON CHEAPER THAN XENON OR KRYPTON.

GAIN LIMIT

$10^3 - 10^4$ FOR ARGON

DURING AVALANCHE MANY EXCITED IONS CREATED (ONLY 11 eV ABOVE SIMPLE IONISATION)

⇒ 11 eV PHOTON WILL BE EMITTED.

PHOTON TYPICALLY HAS MEAN FREE PATH > SIZE OF CELL ⇒ CAN TRAVEL TO CATHODE AND EJECT ELECTRON (WORK FUNCTION OF COPPER ~ 8 eV).

THIS ELECTRON WILL RETURN TO ANODE

⇒ RUNAWAY DISCHARGE.

NEED <u>QUENCHERS</u>

QUENCHERS

POLYATOMIC MOLECULES HAVE ROTATIONAL AND VIBRATIONAL MODES - THESE CAN ABSORB PHOTONS

METHANE (CH_4) ABSORBS IN 8-14 eV RANGE

TYPICALLY ARGON - CH_4 IN 80-20 MIX IS SUITABLE.

POLYMERISATION

- IN THE PROCESS OF ABSORBING PHOTONS POLY ATOMIC QUENCHERS CAN DISSOCIATE

  → POLYMERS

- POLYMERS ARE ATTRACTED TO ANODE OR CATHODE WHERE THEY CAN BUILD UP OVER TIME

- RESULTS IN AGEING → BUILD UP OF INSULATORS ON ANODE OR CATHODE ⇒ NON-UNIFORM ELECTRIC FIELDS.

CAN USE NON-POLYMERISING ADDITIVES LIKE METHYLAL (Ar - Isobutane ($CH_{4\,10}$) BUBBLED THROUGH METHYLAL WAS A STANDARD CHOICE)

NOW USE ARGON - ETHANE (MUCH LESS POLYMERISING)

EXAMPLES OF POLYMER BUILDUP

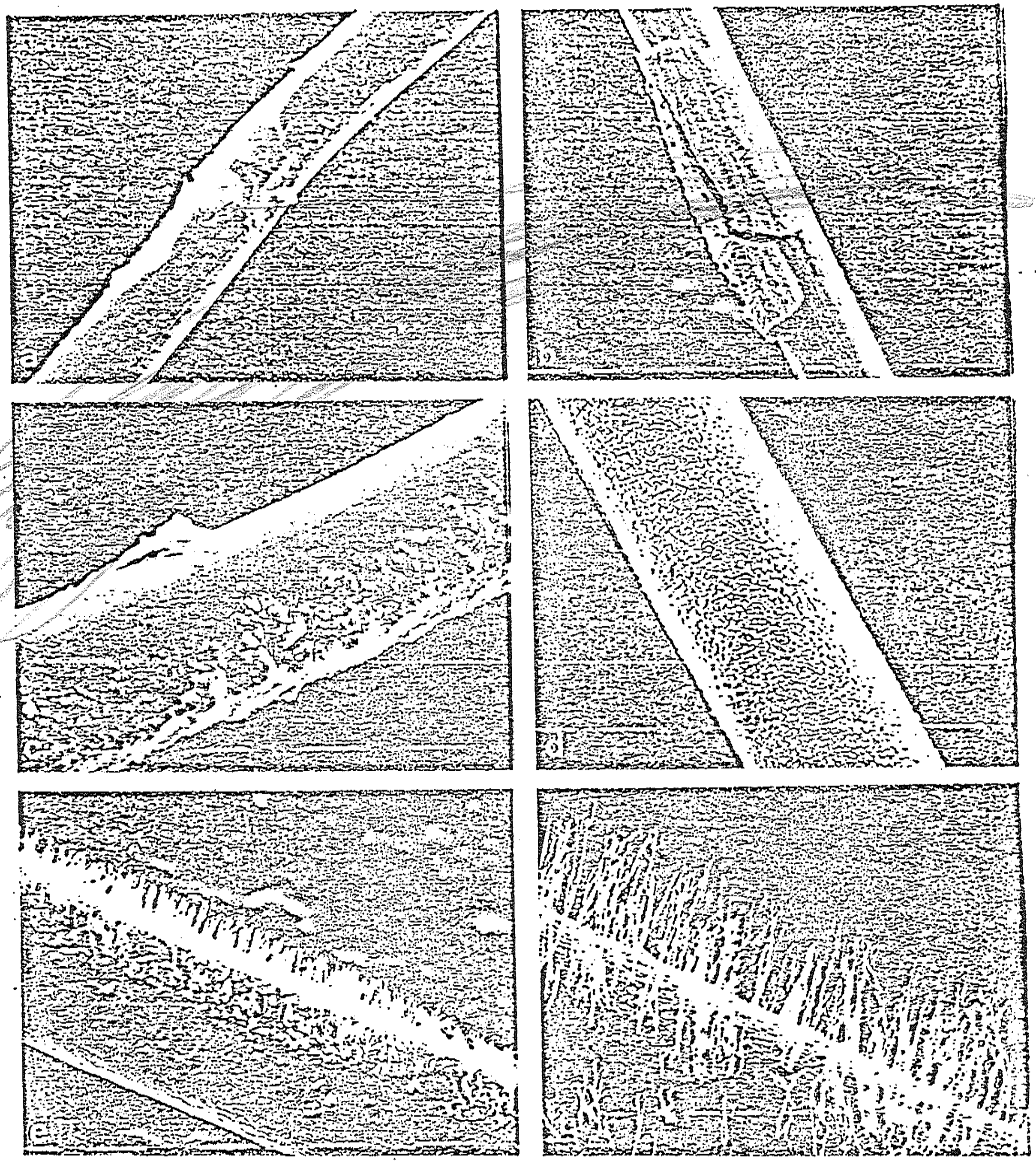
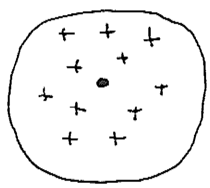


Fig. 6. Deposits on anode wires. (a–c) from the G10 chambers: (a) Ar/C_2H_6; (b)+methylal; (c) Ar/CO_2; (d) from the perspex chamber; (e,f) from the G10 chamber and cold trap.

DEATH IF TOTAL SIGNAL (INCLUDING GAIN) $\gtrsim$ 1 C/cm

SPACE CHARGE GAIN LIMITATION

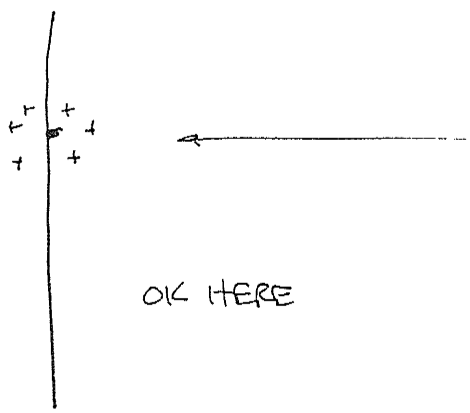
POSITIVE IONS SHIELD ELECTRIC FIELD OF WIRE



GAUSSIAN PILLBOX SURFACE

$E \to 0$

NOMINAL FIELD ONLY RESTORED AFTER IONS $\to$ CATHODE (100's μs).



PROROTIONAL MODE
$\Rightarrow$ LOCAL DEAD REGIONS

GEIGER MODE
$\Rightarrow$ WHOLE TUBE DEAD

HIGH RATE ENVIRONMENTS (eg. CDF run 2, ATLAS)

- EVEN PROPORTIONAL MODE MAY NOT BE GOOD ENOUGH

    - MANY SMALL DEAD REGIONS CAN STILL GIVE FINITE INEFFICIENCIES.

- EVEN MORE SERIOUS FOR A DRIFT CHAMBER
    - DRIFT FIELD BECOMES UNPREDICTABLY DISTORTED.

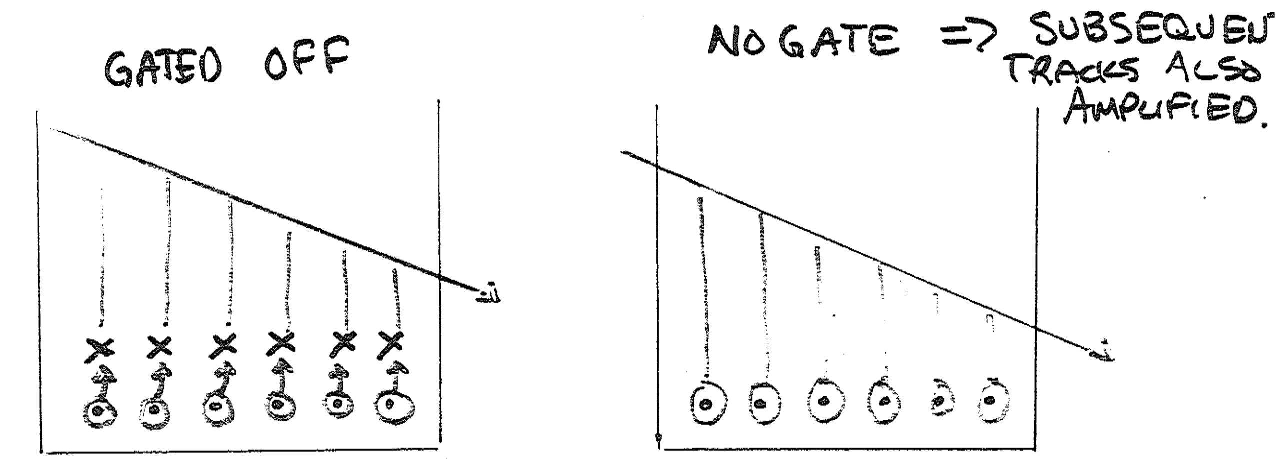
SOLUTIONS TO SPACE CHARGED PROBLEMS

- RUN AT VERY LOW PROPORTIONAL GAIN
  => FEWER POSITIVE IONS

  BUT SMALLER SIGNALS

- WORK WITH SMALLER ANODE/CATHODE GAPS
  => FASTER ION MIGRATION

- GATE OFF THE AMPLIFICATION REGION.



• ANODE WIRES

✗ GATING WIRES

CHANGING VOLTAGES ON GRID BY ±50V BLOCKS OFF AMPLIFICATION REGION => IONS ONLY HAVE TO "RETURN" TO GATING GRID.

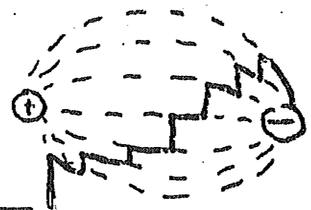
APPLYING ΔV WHEN "INTERESTING TRACKS" ARE PRESENT => ONLY "USEFUL SIGNALS" AMPLIFIED.

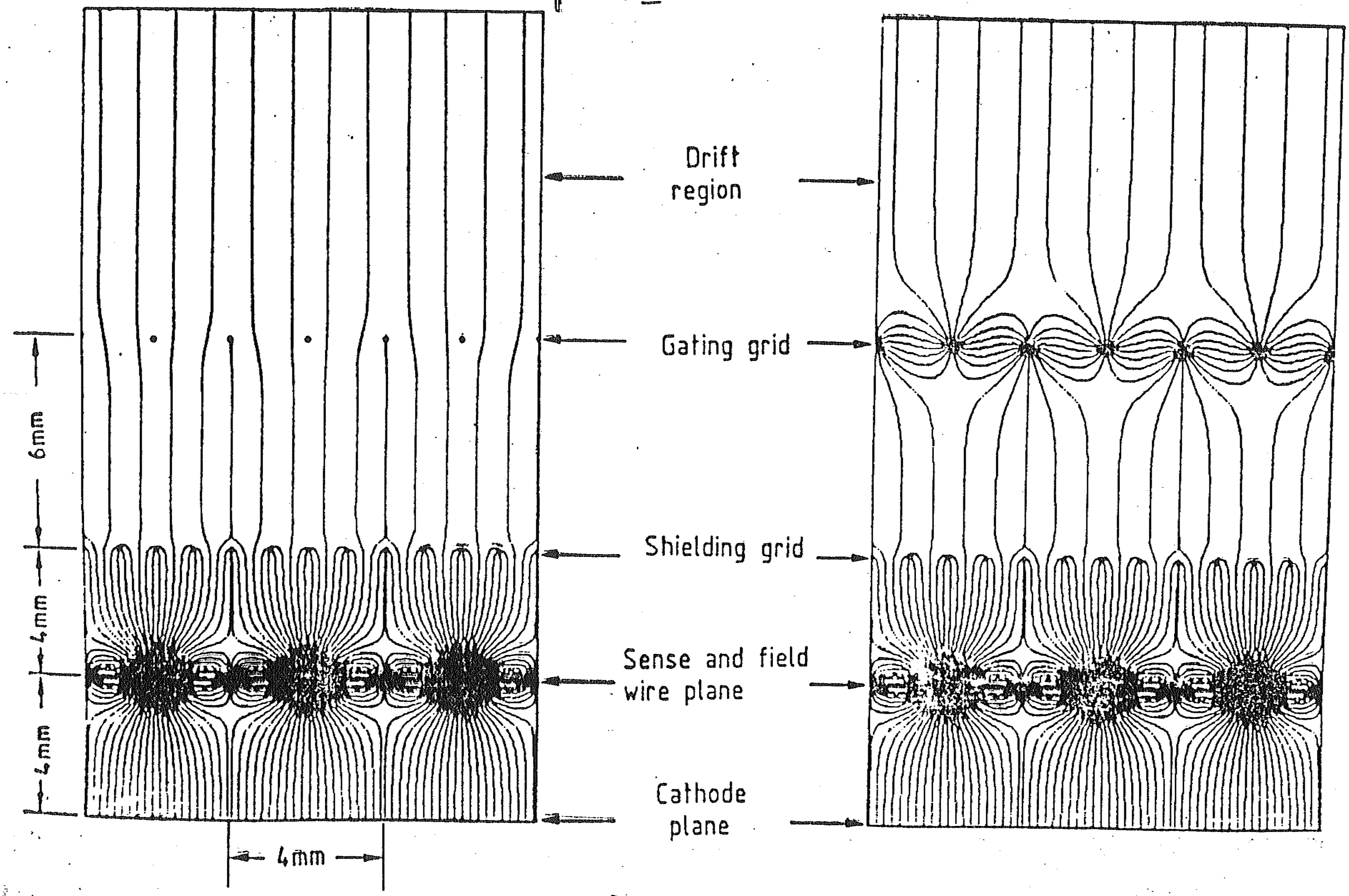
(19)

ALEPH TPC GATES

GATE IS OPENED AND CLOSED BY A SQUARE WAVE TRAIN

IONS ARE FORCED ONTO NEGATIVE WIRE





Figs 2(a)-2(b)

OPEN GATE

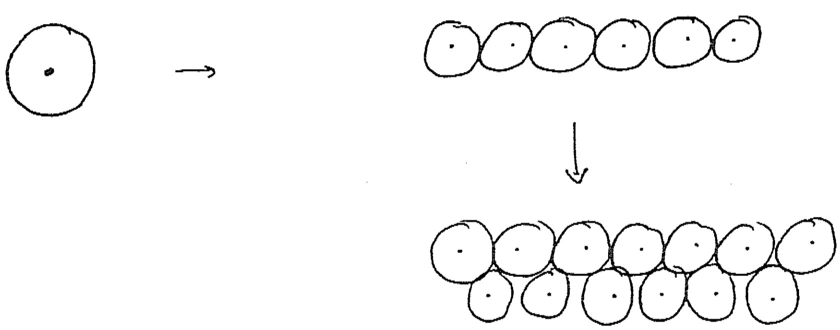
CLOSED GATE

Include in 2024

SOME SPECIFIC EXAMPLES

MULTI-WIRE PROPORTIONAL CHAMBERS (MWPC's)

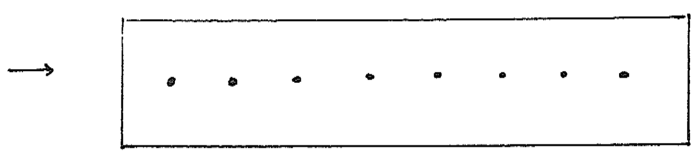
- MOST-OFTEN USED IN FIXED TARGET GEOMETRIES BUT STILL USED IN:
  - BEAM CHAMBERS
  - MUON DETECTORS
  - SOME FINE GRANULARITY CALORIMETER



INTER-TUBE INEFFICIENCIES

BETTER, BUT BULKY.

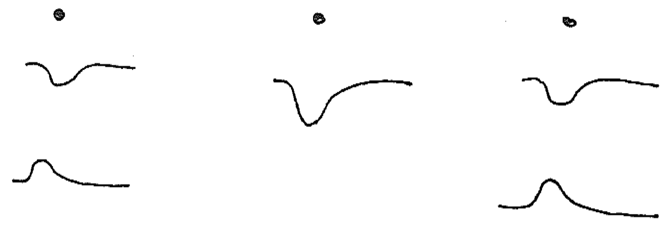
1967 CHARPAK



PUT MANY WIRES IN SINGLE GAS VOLUME.

STUMBLING BLOCK WAS BELIEF THAT SIGNAL ON ONE WIRE WOULD INDUCE SIGNALS ON ALL NEIGHBORING WIRES (CAPACITIVE CROSS-TALK).

IN FACT NEGATIVE "CROSS-TALK" SIGNALS ARE CANCELLED BY MOVEMENT OF POSITIVE IONS INDUCING POSITIVE SIGNALS ON NEIGHBORING WIRES.

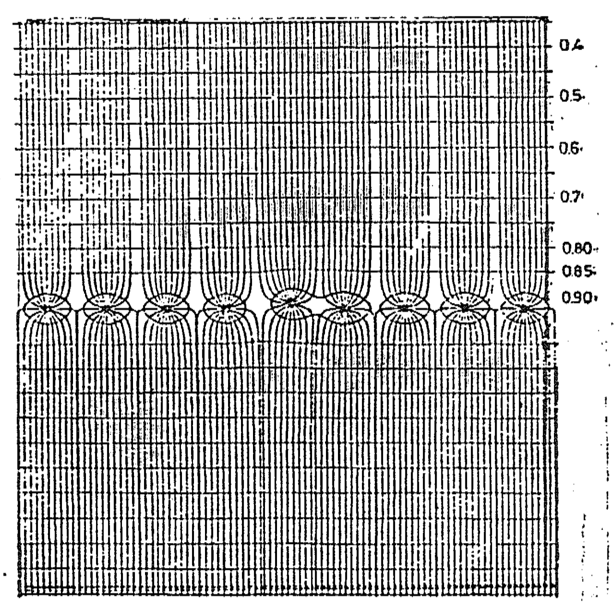


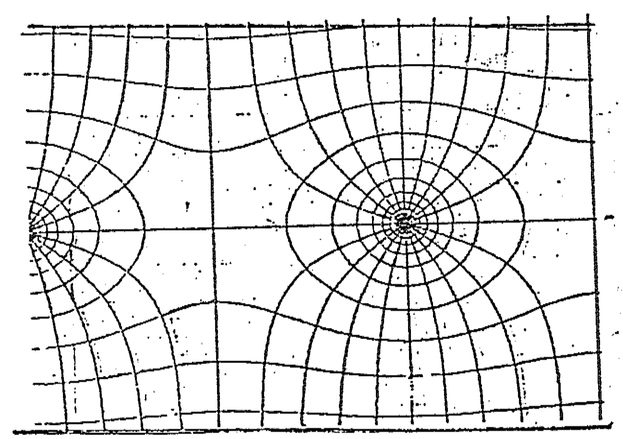
ION INDUCED SIGNAL

CROSS-TALK

THE BOTTOM LINE IS THAT THE ACTUALLY WORK.

TYPICAL FIELD CONFIGURATION

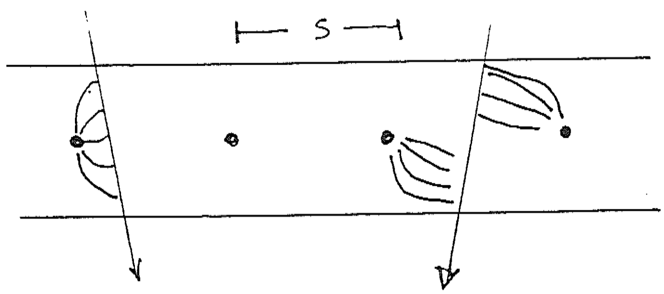




WIRE SPACING 2 mm
WIRE DIAMETER 20 μm

MWPCs (CONTINUED)

- NO TIMING INFORMATION RECORDED
- POSITION IS TAKEN AS THAT OF STRUCK WIRE (SOMETIMES TWO WIRES SHARE SIGNAL => TAKE MIDPOINT BETWEEN THE TWO STRUCK WIRES).



THUS:

RESOLUTION ~ S

$$\sigma = \text{RMS} = \sqrt{\int_{-S/2}^{S/2} (x-\bar{x})^2 dx \Big/ \int_{-S/2}^{S/2} dx}$$

e.g. $\bar{x} = 0$

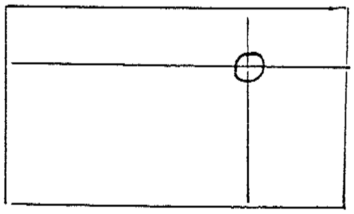
$$= \sqrt{\frac{x^3}{3}\Big|_{-S/2}^{S/2} \Big/ x\Big|_{-S/2}^{S/2}}$$

$$= \frac{S}{\sqrt{12}}$$

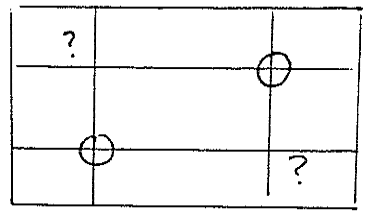
PITCH $/\sqrt{12}$ IS THE STANDARD AGAINST WHICH ALL WIRE CHAMBER PERFORMANCES ARE JUDGED.

CHAMBER SYSTEMS

- TWO CONSECUTIVE PLANES CAN BE USED TO DEFINE A POINT

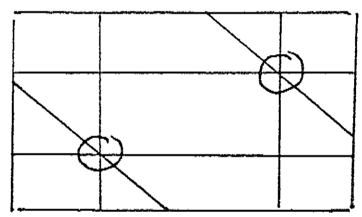


FOR MULTIPLE TRACKS



X, Y

NEED TO ADD A <u>THIRD</u> NON-PARALLEL PLANE



X, Y & U or V.

ANOTHER WAY TO GAIN ADDITIONAL INFORMATION IS TO SEGMENT AND READOUT THE CATHODE

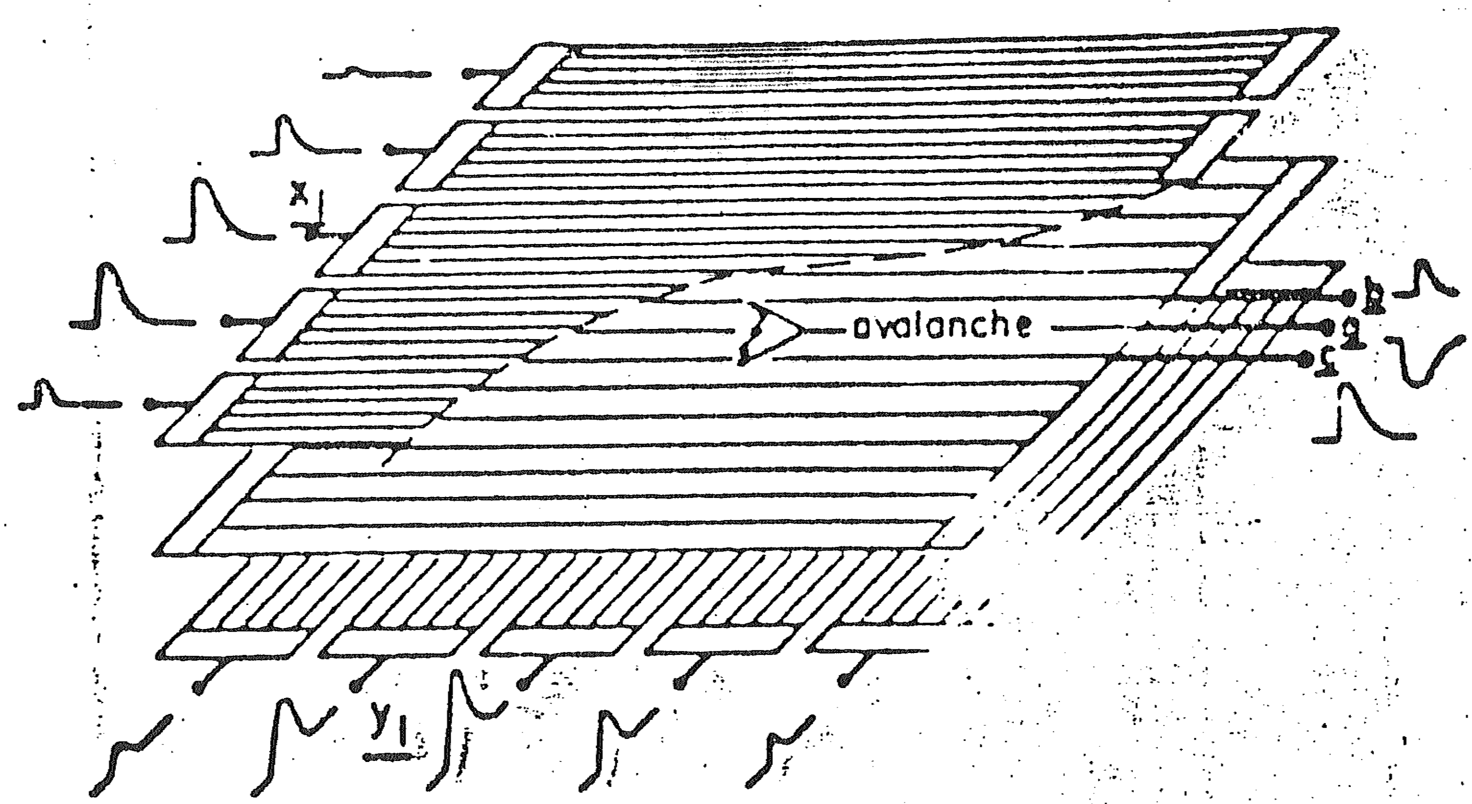
AVALANCHE ON WIRE CAUSES POSITIVE PULSES ON NEIGHBORING CATHODE ELECTRODES.

NOTE: TYPICALLY CELL THICKNESS $\sim$ 4 x PITCH
(CAPACITANCE & PRIMARY IONISATION)

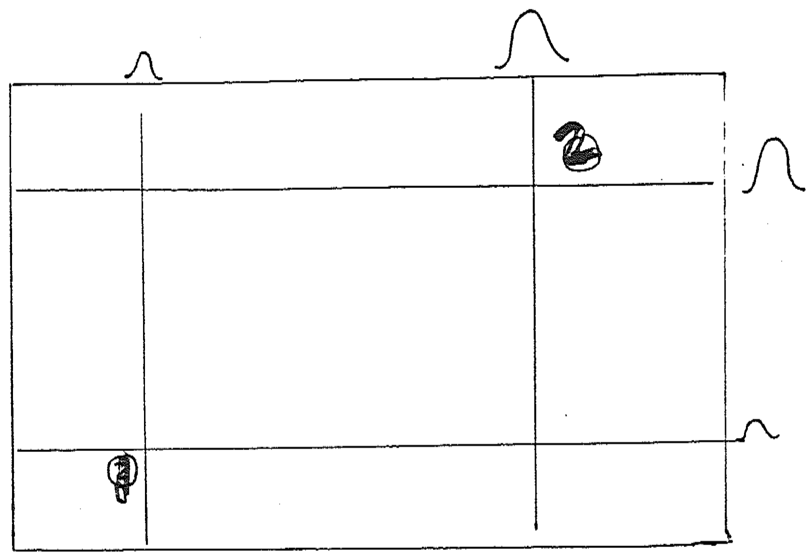
$\Rightarrow$ SIGNAL SPREADS OVER $\simeq$ 4 x LARGER AREA.

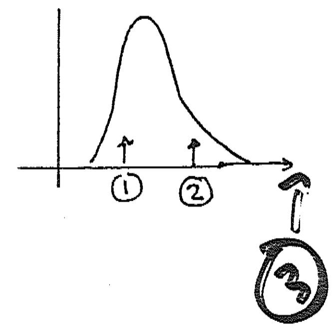
SEGMENTED CATHODES

CATHODE TYPICALLY 3-4 x FURTHER AWAY FROM WIRE THAN WIRE SPACING (s) ⇒ SIGNALS MORE SPREAD OUT. USE CENTRE OF GRAVITY MEASUREMENT.



MULTIPLE TRACKS WITH CATHODE READOUT





CORRELATE LANDAU FLUCTUATIONS

ONLY POSSIBLE WHEN SIGNALS RESULT FROM THE SAME AVALANCHE. IE CATHODE AND ANODE OF SAME CHAMBER.

IN PRACTICE THIS PROCEDURE IS LIMITED BY THE S/N OF THE READOUT. IF THE

NOISE IN THE READOUT SYSTEM IS COMPARABLE TO THE PROBABLE LANDAU FLUCTUATIONS THEN VERY FEW AMBIGUITIES CAN BE RESOLVED THIS WAY.

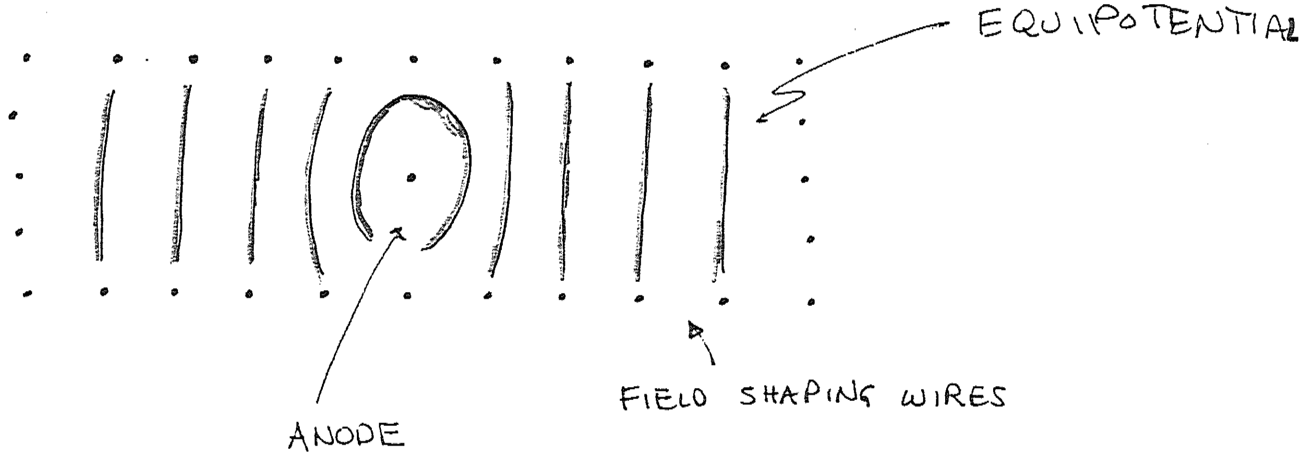
DRIFT CHAMBERS

BASIC IDEA : MEASURE ARRIVAL TIME OF CHARGE AT ANODE (W.R.T. EXTERNAL TRIGGER) TO

1) IMPROVE POSITION RESOLUTION

OR

2) EXTEND SENSITIVE AREA OF A SINGLE WIRE / REDUCE READOUT CHANNELS.



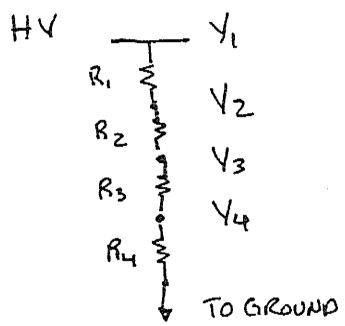
NEED UNIFORM DRIFT FIELD TO HAVE A RELIABLE d vs. t RELATIONSHIP.

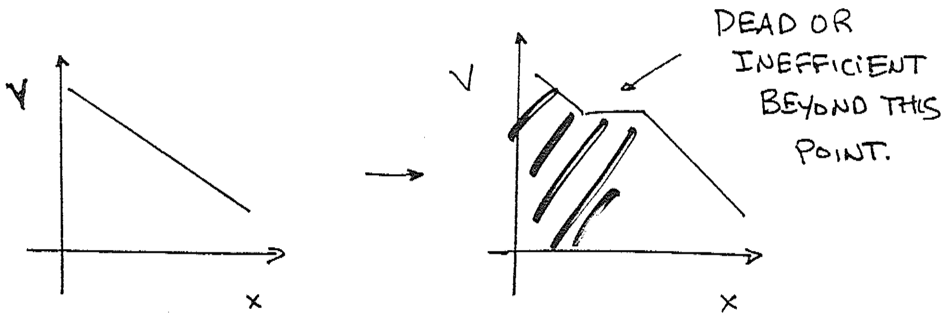
ALWAYS LIMITED BY CHANGING FIELD IN AMPLIFICATION REGION.

- TO A LESSER EXTENT VERY LONG DRIFTS (FROM EDGE OF CELL) ALSO PROBLEMATIC.

Skip in 2024

POSSIBLE PROBLEMS WITH FIELD SHAPING

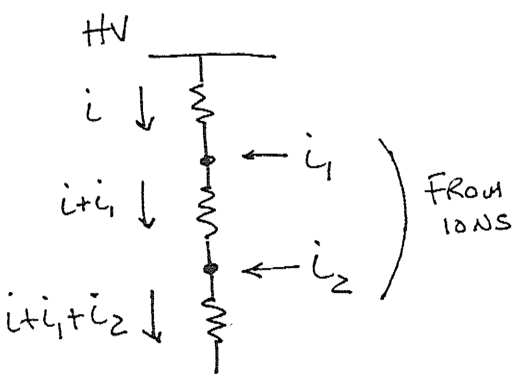


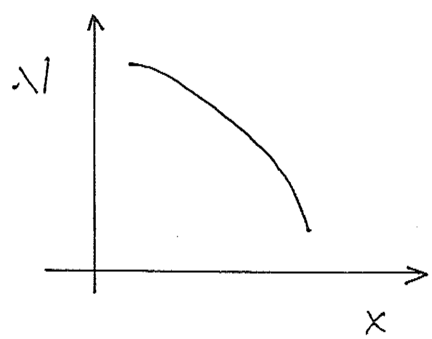


IF R_N SHORTS $V_N = V_{N+1}$

IF R_N OPEN WHOLE CELL DEAD

IN HIGH RATE OPERATION IONS BEGIN TO NEUTRALISE ON DIVIDER CHAIN



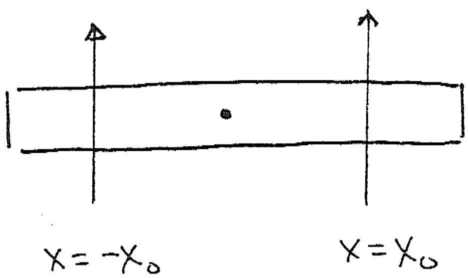


NEED HIGH CURRENT CHAIN $i \gg i_1, i_2$.

ALSO CAN HAVE PROBLEMS IF FIELD SHAPING WIRES NEAR INSULATING MATERIAL (CHAMBER WALLS) POSITIVE IONS CAN CHARGE UP NEAR FIELD WIRES $\Rightarrow$ UGLY DRIFT FIELD.

Include in 2024

LEFT - RIGHT AMBIGUITY

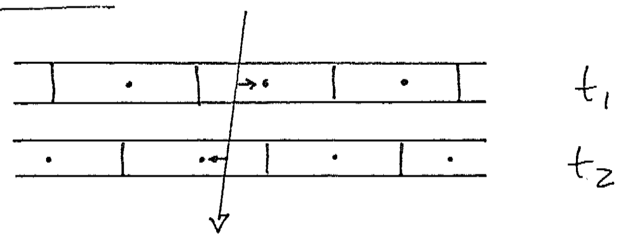


$t = |x|/w = x_0/w$

WHICH SIDE?

SOLUTIONS

1)



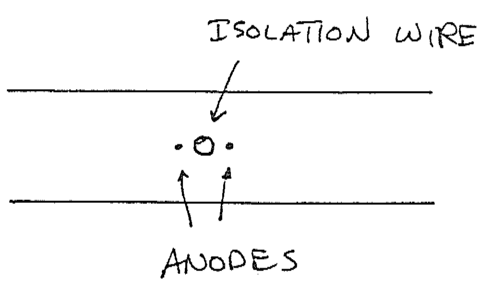
CLOSER THE BETTER
ESPECIALLY FOR ANGLED
TRACKS

FOR NORMAL ($\perp$) TRACKS

$t_1 + t_2 = \text{CONSTANT} = \dfrac{\text{CELL SIZE}}{w}$

$\Rightarrow$ CALIBRATION.

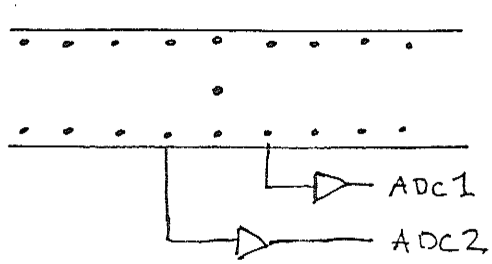
2)



2 ANODE WIRES

2x READOUT ELECTRONICS.

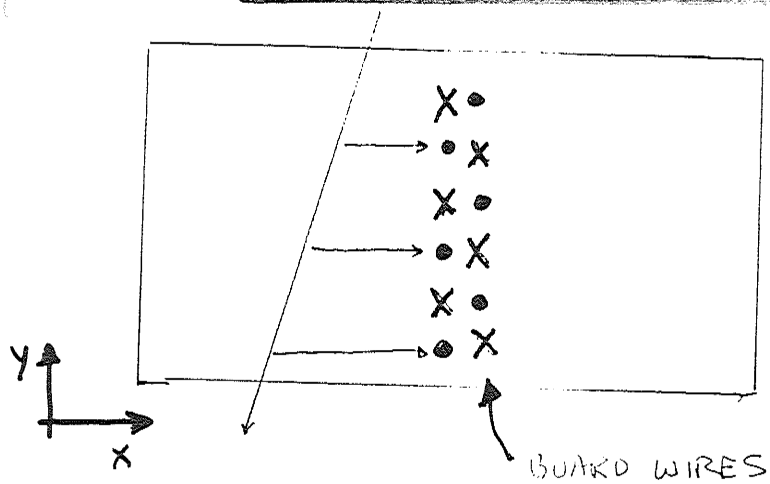
3)



READOUT LAST
FIELD SHAPING WIRES

3x ELECTRONICS

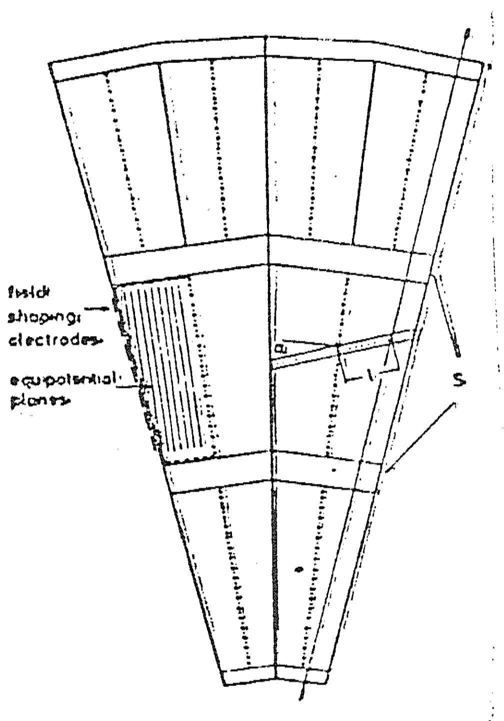
MULTIPLE ANODE DRIFT CELLS

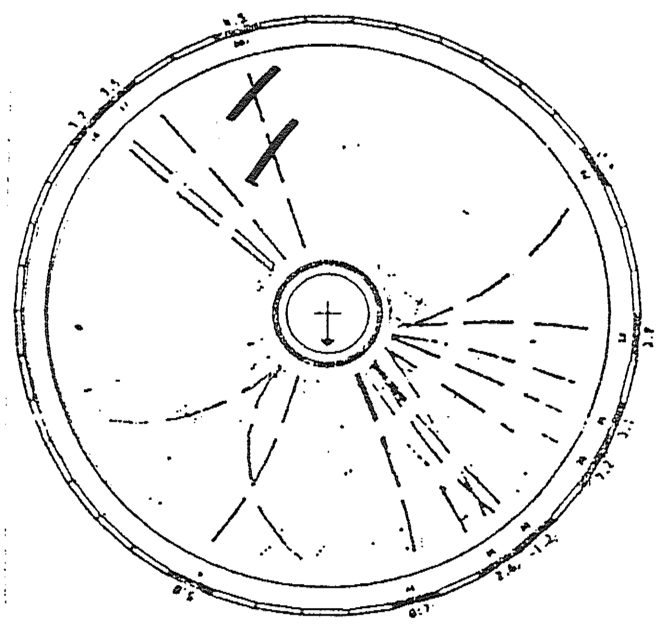


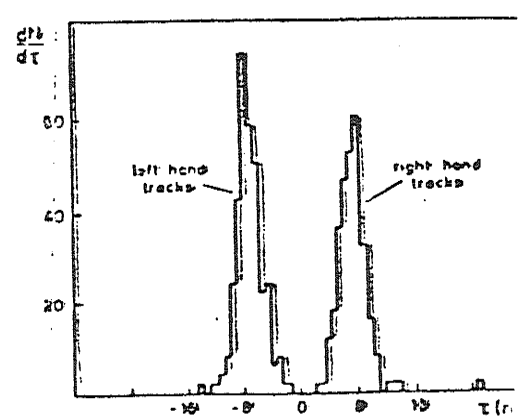
3 ANODES FOR LEFT

3 ANODES FOR RIGHT

SLOPE & POSITION FROM A SINGLE CELL







JET CHAMBER

(JADE, OPAL, ...)

4 left/right separation > position resolution

Skip in 2024

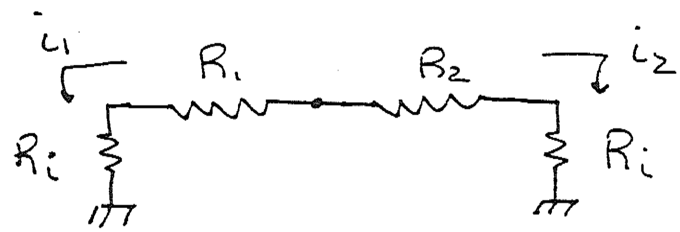
DETERMINING THE THIRD COORDINATE

x GIVEN BY DRIFT TIMING

y GIVEN BY WIRE POSITION

z ?

CHARGE DIVISION



INTEGRATE i_1, i_2

$\rightarrow Q_1, Q_2$

$$i_1(R_i+R_1) = i_2(R_i+R_2)$$

$\vdash$ L $\dashv$

$\vdash$ z-1

$$\frac{Q_1}{Q_2} = \frac{R_i+R_2}{R_i+R_1} = \frac{R_i+\rho z}{R_i+\rho(L-z)}$$

TAKE $z_i = R_i/\rho$ EQUIVALENT LENGTH OF WIRE IN AMPLIFIER INPUT

$$\Rightarrow z = z_i\frac{(Q_1-Q_2)}{(Q_1+Q_2)} + L\frac{Q_1}{(Q_1+Q_2)}$$

$\uparrow$

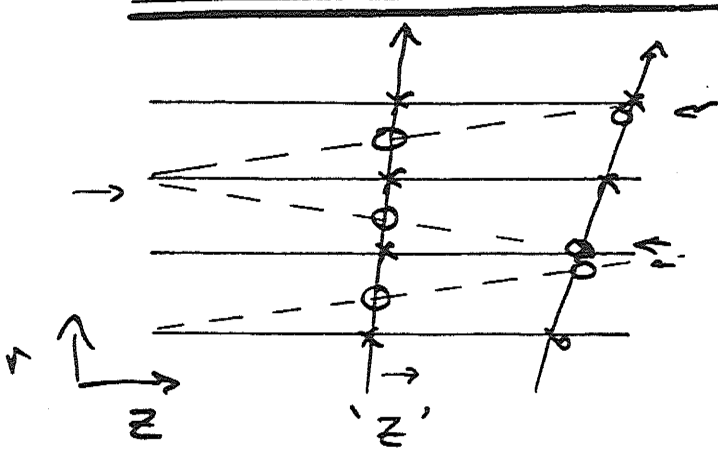
MAKE SMALL WITH HIGH ρ WIRE OR LOW R_i AMPLIFIER

TYPICALLY δQ_i GOOD ENOUGH TO MAKE $\sigma_z \lesssim 1\%\, L$

0.5% in OPAL $\sim$ 1 cm in 2.0 m WIRES.

ATLAS-SCT !

STEREO WIRES (CDF, ZEUS, OPAL VTX)



ALTERNATING LAYERS

0
$+\theta$
0
$-\theta$
0
etc.

TYPICALLY ANGLES OF A FEW DEGREES

($6^\circ \simeq 100$ mrad $\Rightarrow$ $\sigma_z \simeq 10\,\sigma_{r\phi}$)

$= \dfrac{\sigma_{r\phi}}{\theta_{stereo}}$

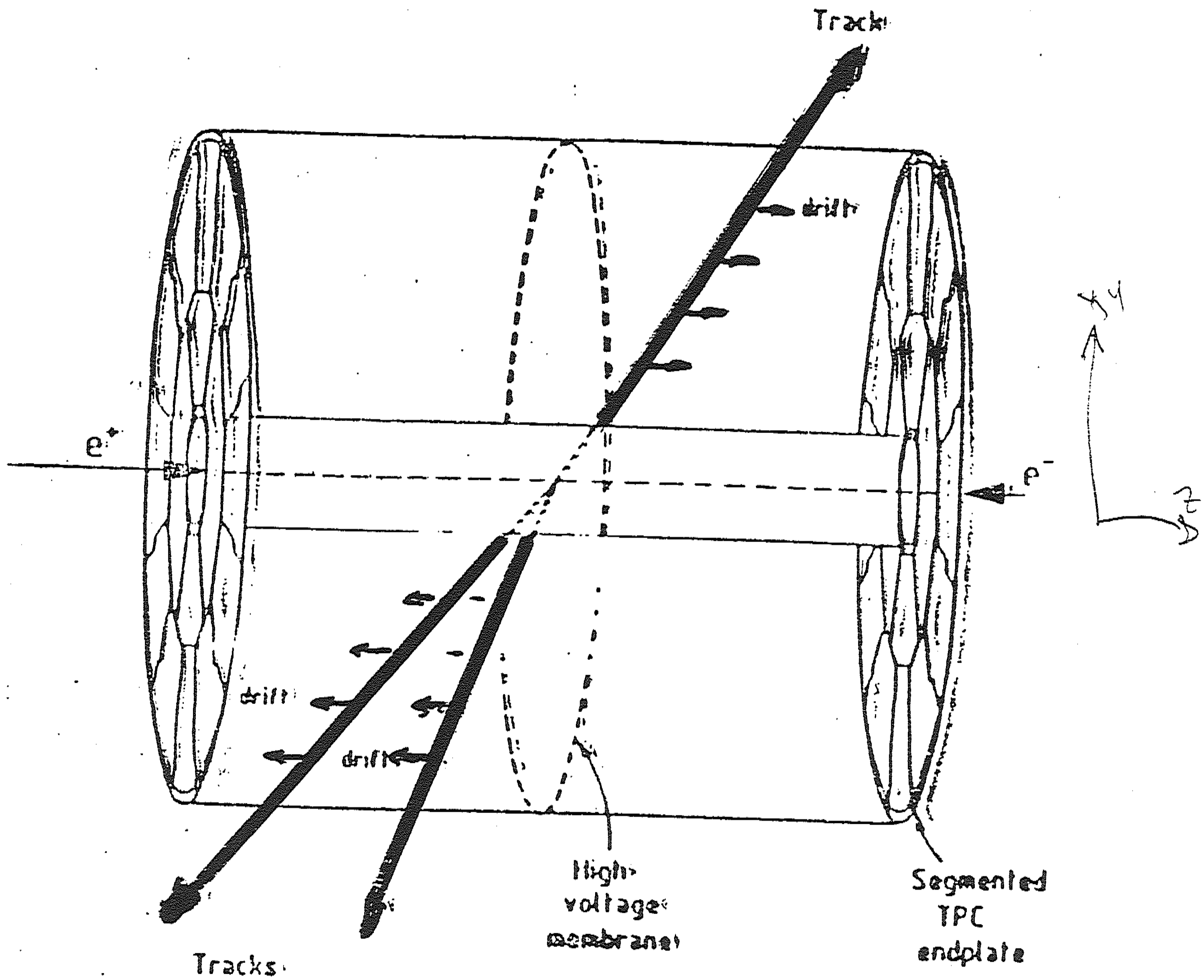
ADVANTAGES : $\sigma_z \lesssim 1$ mm
WITHOUT Q MEASUREMENT
WITHOUT FAST TIMING

DISADVANTAGES : INFORMATION ONLY AVAILABLE WHEN TRACK FOUND IN AXIAL WIRES.

PATTERN RECOGNITION COMPLICATED
$\Rightarrow$ TIME CONSUMING $\Rightarrow$ NOT AVAILABLE ONLINE.

theta_SCT = 40mrad sigma_z = 25 sigma_rphi = 1.2mm

TIME PROJECTION CHAMBER (ALEPH, DELPHI) ILD



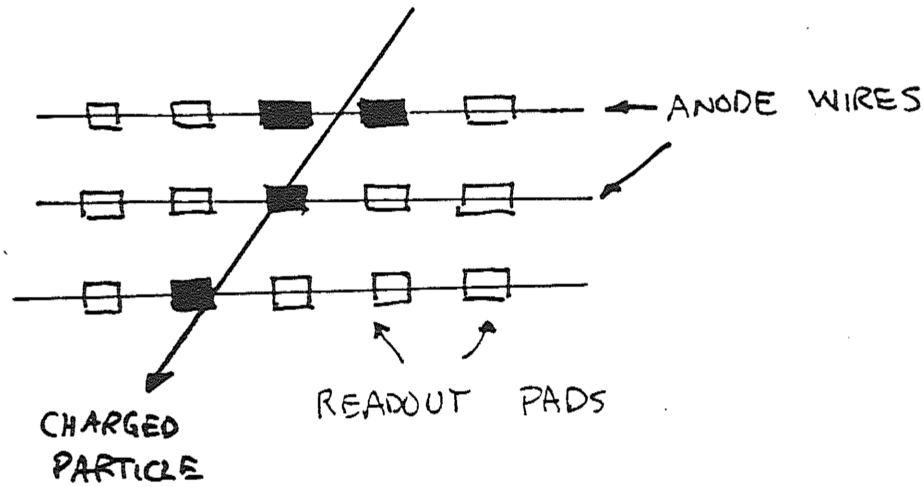
- MEASURE z, θ FROM DRIFT TIME
- MEASURE r, ϕ FROM PADs & WIRES READOUT ON ENDPLATES

EFFECTIVELY DIVIDE SPACE INTO 3D PIXELS

⇒ GOOD FOR PATTERN RECOGNITION IN ~~U~~MEDIUM MULTIPLICITY ENVIRONMENTS.

7)

PAD / WIRE READOUT ON ENDPLATES



- WELL ADAPTED TO COMPLEX TOPOLOGIES

- BASE PATTERN RECOGNITION ON PADS.

- WIRES NECESSARY FOR SIGNAL AMPLIFICATION / AVALANCHE BUT CAN SUFFER MULTI-HITS ⇒ PATTERN RECOGNITION CONFUSED

OFTEN ADD "EXTRA WIRES" ⇒ MANY SAMPLES OF LANDAU DISTRIBUTION FOR ISOLATED TRACKS (SEE PARTICLE ID LATER)

ENORMOUS NUMBER OF CHANNELS FOR PADS N^2 (COMPARED TO 2N FOR CROSS-WIRES)

BUT GIVES 3D INFO SO PERHAPS NOT SO WASTEFUL.

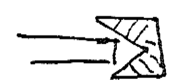
USE C.C.D.s TO BUFFER INFO.

DRIFT TIME CALIBRATION

TPCs PROVIDE MOST STRINGENT REQUIREMENT ON DRIFT DISTANCE VS. TIME RELATIONSHIP.

I
P.

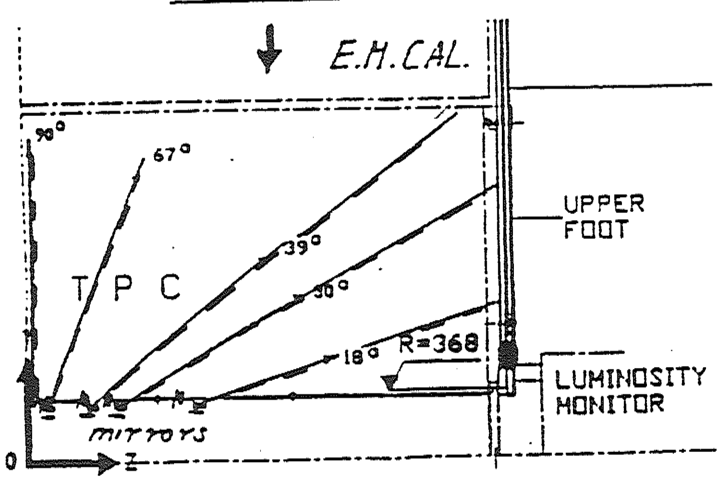
1) USE UV LASERs (e.g. NITROGEN
$\lambda = 330\ nm$
$E \approx 3\ eV$)

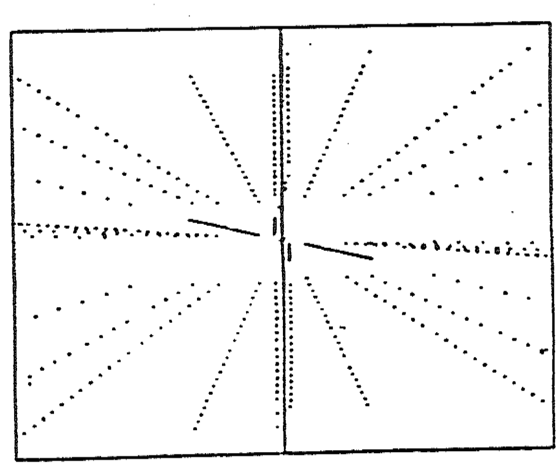
ADVANTAGES:
- INSENSITIVE TO $|\vec{B}|$
- " MULTIPLE SCATTERING
- NO LANDAU FLUCTUATIONS
- PULSE HEIGHT ADJUSTABLE
- TWO TRACK RESOLUTION 

PROBLEM: $E_{ION} > E_{\gamma}$

$\Rightarrow$ 2γ PROCESSES OR IONIZING UN-INTENTIONAL IMPURITIES.

ALEPH

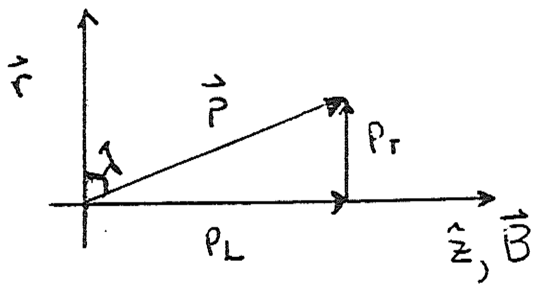




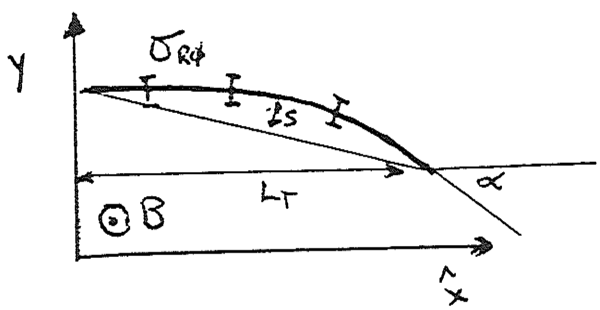
Include in 2024

MOMENTUM MEASUREMENT

CHARGED PARTICLE FOLLOWS HELICAL TRAJECTORY IN MAGNETIC FIELD (TAKE EXAMPLE OF SOLENOIDAL MAGNETIC FIELD)



$$P_T = P \cos \lambda$$



$$p_T = 0.3 \; B \cdot R_T$$

[GeV/c] [T] [m]

$Q=1$

Can approximate:

$$S \simeq \frac{L_T^2}{8R_T} \qquad \alpha \simeq \frac{L_T}{R_T}$$

(GLUCKSTERN NIM 24 (1963) 381)

MOMENTUM RESOLUTION

$$\left(\frac{dp}{p}\right)^2 = \left(\frac{\sigma_{R\phi}\ a_n}{L_T^2\ 0.3B}\right)^2 P_T^2$$ FROM $\sigma_{R\phi}$ ON S

$$+ \left(\frac{\sigma_z\ f_n \sin\lambda \cos\lambda}{L_T}\right)^2$$ FROM σ_z ON λ

$$+ \left(\frac{0.053}{B\ \beta \cos\lambda \sqrt{L_T X_0}}\right)^2$$ FROM MULTIPLE SCATTERING

→ FOR EVENLY SPACED MEASUREMENTS (BEST FOR MULTIPLE SCATTERING)

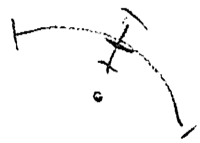
n	3	12	100	n	$n>10$
a_n	9.8	6.6	2.6	$\sqrt{\frac{720(n-1)^3}{(n-2)\,n\,(n+1)(n+2)}}$	$\sqrt{\frac{720}{(n+4)}}$

→ FOR $n/2$ MEASUREMENTS IN "MIDDLE"

$n/4$ MEASUREMENTS AT $\pm L_T/2$

$$a_n' \simeq \sqrt{\frac{256}{n}}$$ => 40% TO BE GAINED IF MULT. SCATT NOT A PROBLEM

EXAMPLES



$$\frac{dp_T}{p_T} = \frac{\sigma_{R\phi}}{s}$$ FOR 3 POINTS

$$\frac{dp_T}{p_T} = \frac{p_T}{0.3B}\,\frac{\sigma_{R\phi}\, a_n}{L_T^2} \simeq 1\%\, p_T$$

$L_T = 1\,m$
$B = 1\,T$
$n = 3$
$\sigma_{R\phi} = 300\,\mu m$

$$\frac{dp_T}{p_T} = 0.1\%\, p_T$$ CDF

1 - 100 GeV

$L_T = 1.35\,m$
$B = 1.4\,T$
$n = 100$
$\sigma_{R\phi} \simeq 300\,\mu m$

$$\frac{dp_T}{p_T} = 0.1\%\, p_T$$ DELPHI

1 - 20 GeV

$L_T = 1.5\,m$
$B = 1.2\,T$
$n = 20$
$\Rightarrow \sigma_{R\phi} \simeq 150\,\mu m$

$$\frac{dp_T}{p_T} = 0.01\%\, p_T$$ ATLAS

OPTIMISTIC

$a_{10}' = 5.0$

10 - 1000 GeV

$L_T = 1.1\,m$
$B = 2\,T$
$n = 10$
$\Rightarrow \sigma_{R\phi} = 15\,\mu m$

OTHER TERMS ?

(2) $f_n = \sqrt{\dfrac{12\,(n-1)}{n\,(n+1)}}$ $\qquad n = 10 \Rightarrow f_n \simeq 1$

$\qquad\qquad n = 100 \qquad \simeq 0.3$

$\sin\lambda \cos\lambda \leq 1/2$

$\sigma_z \lesssim$ mm $\Rightarrow$ SECOND TERM $\lesssim 10^{-3}$ INDEPENDENT OF p

(3) $$\left(\frac{dp}{p}\right)_{m.sc.} = \frac{0.053}{B\beta \cos\lambda \sqrt{L \cdot X_0}} \qquad \beta = v/c$$

$B = 1\,T$

$L = 1\,m$

$X_0\,(Ar) = 14.0\,cm$ $\qquad \left(\frac{dp}{p}\right) = 0.5\%$

$(Air) = 36\,cm$

$(CO_2) = 26\,cm$

$(He) = 7.6\,m$ $\qquad \left(\frac{dp}{p}\right) = 0.1\%$

IF YOU ARE WORRIED ABOUT 0.1 — 1.0 GeV/c TRACKS THIS WILL DOMINATE

CHOOSE He (CLEO III, BABAR, ...

ELECTRON DRIFT IN $(\vec{E} \times \vec{B})$

FOR $|\vec{E}|$ CONSTANT IN GASES   EQUATE ACCELERATION

$$\frac{\vec{v}_D}{\tau} + \frac{e}{m_e}(\vec{B} \times \vec{v}_D) = \frac{e\vec{E}}{m_e}$$

τ = MEAN TIME BETWEEN COLLISIONS

$$\Rightarrow \vec{v}_D = \frac{\mu(E)}{1+\omega^2\tau^2}\left(\vec{E} + \frac{\vec{E}\times\vec{B}}{|\vec{B}|}\omega\tau + \frac{(\vec{E}\cdot\vec{B})\vec{B}}{|\vec{B}|^2}\omega^2\tau^2\right)$$

$$\omega = \frac{e|\vec{B}|}{m_e}$$ (cyclotron Frequency)

B=1T

FOR: $\omega\tau \ll 1$ ELECTRONS FOLLOW $(\vec{E})$ CO_2

$\omega\tau \gg 1$ ELECTRONS FOLLOW $(\vec{B})$ Ar/CH_4

TYPICALLY A MIXTURE!

LORENTZ ANGLE

$$\vec{E} = (E_x, 0, 0)$$
$$\vec{B} = (0, 0, B_z)$$

$$V_x = \mu E_x \frac{1}{(1+\omega^2\tau^2)}$$

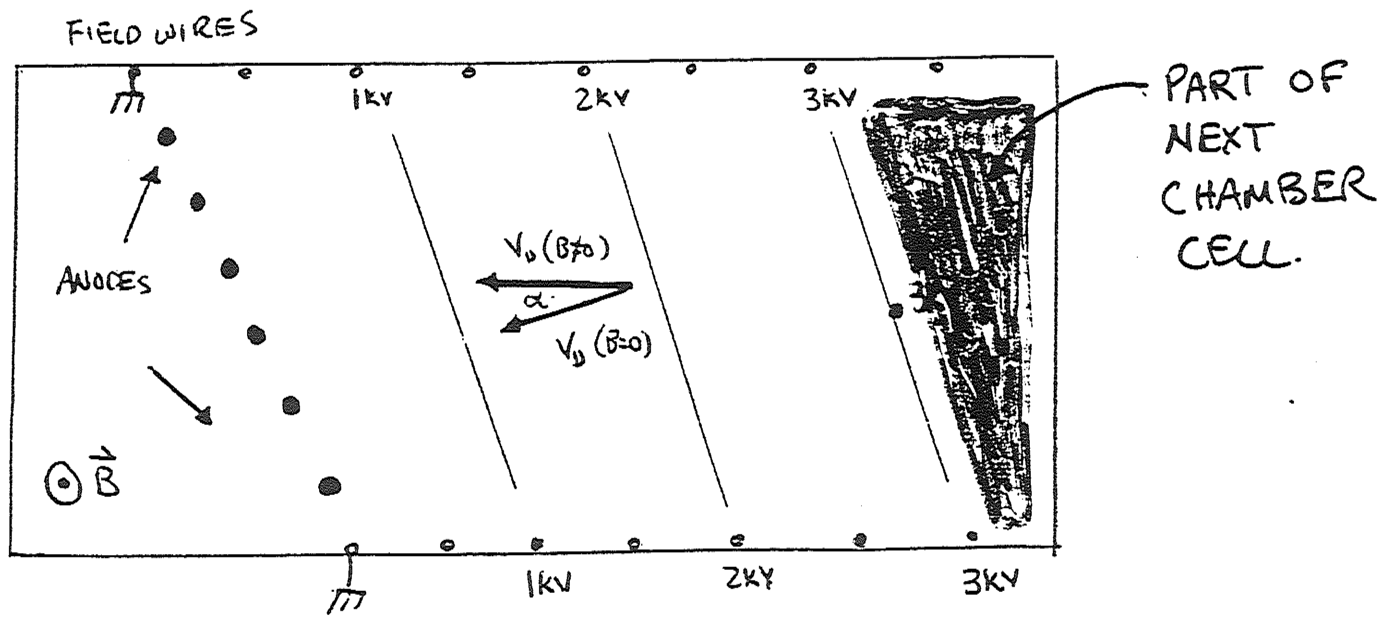
$$V_y = -\mu E_x \frac{\omega\tau}{(1+\omega^2\tau^2)}$$

$$\Rightarrow \quad V_D = \sqrt{V_x^2 + V_y^2} = \mu E_x \frac{1}{\sqrt{1+\omega^2\tau^2}}$$
$$= \mu E_x (\cos \alpha_L)$$

$$\tan(\alpha_L) = \omega\tau \qquad \text{(LORENTZ ANGLE)}$$

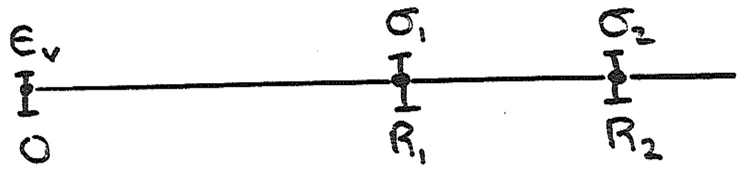
USEFUL 1ST APPROXIMATION

COMPENSATE WITH SKEWED ELECTRIC FIELD



Impact Parameter Resolution

Can be derived from simple extrapolation of a line/propagation of uncertainties:



$$\epsilon_v = \sqrt{\left(\frac{R_1 \sigma_2}{(R_2-R_1)}\right)^2 + \left(\frac{R_2 \sigma_1}{(R_2-R_1)}\right)^2} = \sqrt{R_1^2 + R_2^2}\ \frac{\sigma}{\Delta R}$$

Lessons:

i) Make R_1 as small as possible.

ii) Make σ as small as possible.

iii) Make R_2 as large as possible.

When particle crosses material it scatters adding additional error in estimating the impact parameter.

$$\theta_{SCATTER} \simeq \frac{14}{p(\mathrm{GeV})}\sqrt{\frac{t}{X_0}} \quad (\mathrm{mrad})$$

$$\epsilon_v^{SCATTER} \simeq \frac{1\ \mathrm{mrad}}{p} \cdot R_1$$

FOR TYPICAL BEAMPIPE + FIRST SILICON LAYER @ 1% X_0

SPECIFIC EXAMPLES

THE DELPHI TRACKER (ACTUAL PERFORMANCE)

1) 3 LAYERS SILICON MICROSTRIPS $(r = 6 - 11\ cm)$

$\sigma_{r\phi} \simeq 8\ \mu m$ per point

$\sigma_{rz} \simeq 13 - 25\ \mu m$ (FUNCTION OF θ)

2) 24 WIRE JET CHAMBER $(r = 12 - 23\ cm)$

$\sigma_{r\phi} \simeq 40\ \mu m$ (Σ' 24 points)

3) 5 LAYERS OF STRAW TUBES $(r = 24 - 28 cm)$

DESIGNED AS A TRIGGER

4) TPC WITH 16 PAD ROWS $(r = 40 - 110 cm)$

$\sigma_{r\phi} = 250\ \mu m$

$\sigma_{rz} = 880\ \mu m$ (over $\lesssim$ 1.34 m drift drift)

5) 5 LAYERS OF PROPORTIONAL TUBES

CROSS-CHECK OF TRACK OUTSIDE R.I.C.H.

RESULTS (DELPHI TRACKER)

① IMPACT PARAMETER RESOLUTION:

- DOMINATED BY SILICON

$$\sigma_{r\phi}^{1\,\text{track}} = 20\ \mu m \qquad P_T \gtrsim 5\ \text{GeV}/c$$

$$\sigma_z^{1\,\text{track}} = 60\ \mu m \qquad (@\ 90^\circ)$$

(OTHER DETECTORS CONTRIBUTE < 10% TO I.P. WEIGHT)

② MOMENTUM RESOLUTION

$$\frac{\sigma_p}{p} = (0.6 \times 10^{-3})\ p \qquad (p \text{ in GeV}/c)$$

NB: TPC ALONE ⇒ 7×10^{-3}

SILICON + OUTER TUBES ⇒ L_{TRACK} 0.7m → 1.9 m

$$\Rightarrow \left.\frac{\sigma_p}{p^2}\right)_{TOTAL} \rightarrow \left(\frac{0.7}{1.9}\right)^2 \left.\frac{\sigma_p}{p^2}\right)_{TPC}$$

$$\simeq 1 \times 10^{-3}.$$

⇒ SILICON (+ TUBES) $\sigma_{r\phi} < 250\ \mu m$.

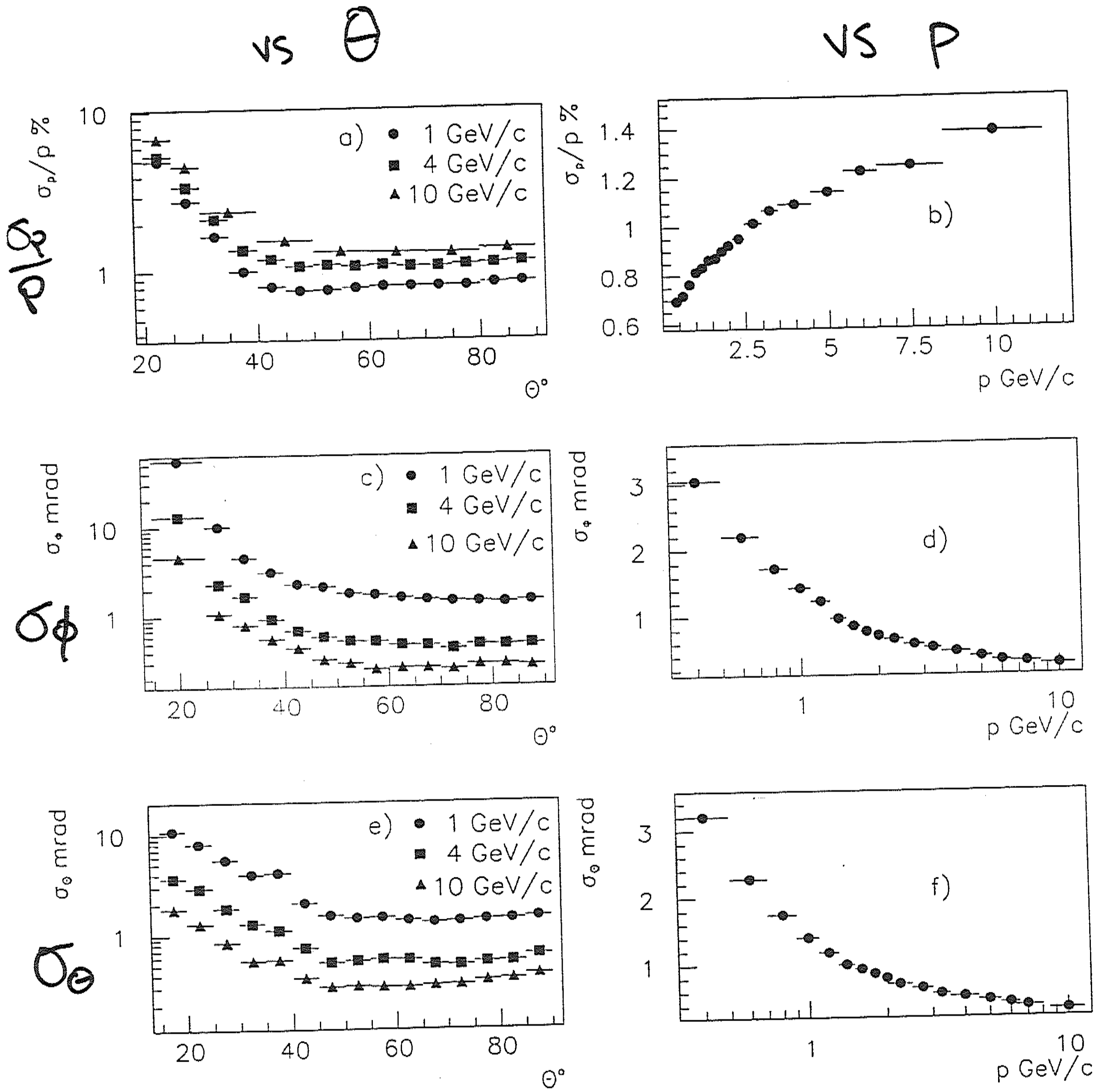
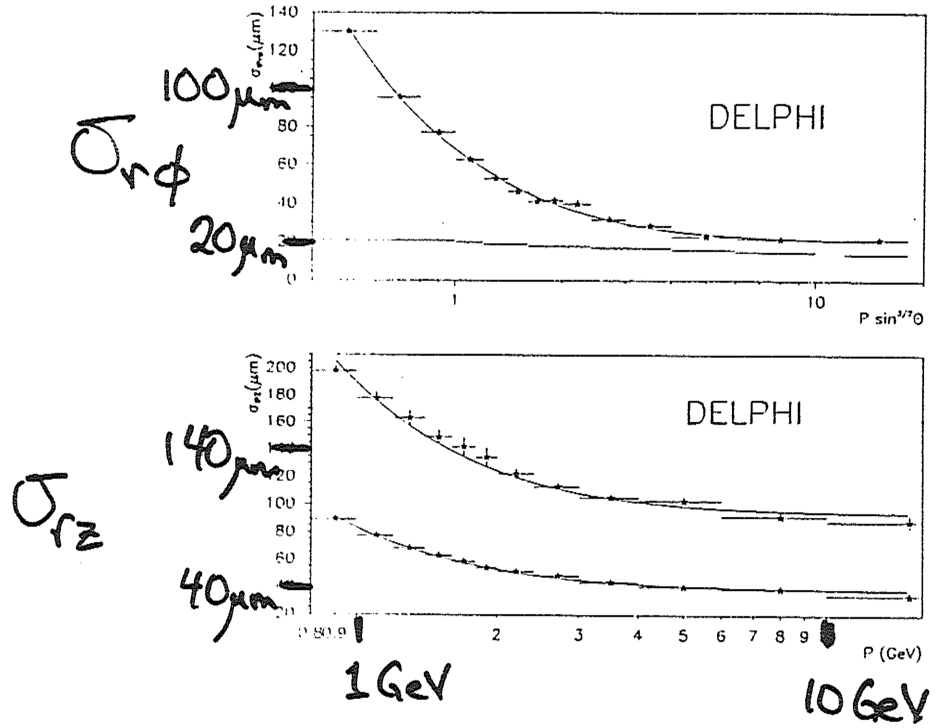


Figure 9: Track parameter precisions estimated by comparing simulated and reconstructed parameters: (a) momentum precision as a function of the polar angle θ, (b) momentum precision as a function of the momentum for barrel tracks, (c) azimuthal angle precision as a function of θ, (d) azimuthal angle precision as a function of the momentum for barrel tracks, (e) polar angle precision as a function of θ, (f) polar angle precision as a function of the momentum for barrel tracks.

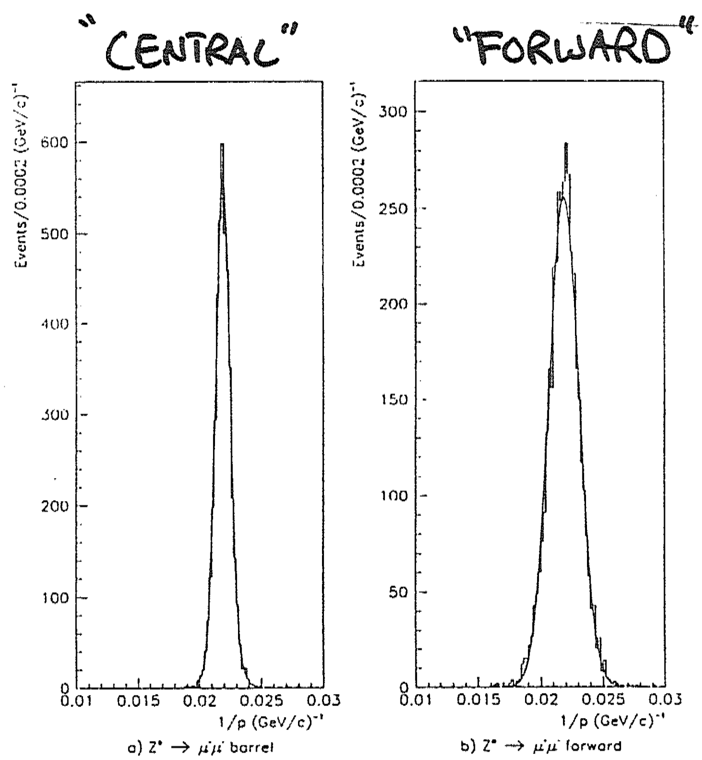
IMPACT PARAMETER RESOLUTION



MOMENTUM RESOLUTION

$\theta(°)$	Detectors	$\sigma(1/p)(\mathrm{GeV}/c)^{-1}$
≥ 42	VD+ID+TPC+OD	0.6×10^{-3}
≥ 42	ID+TPC+OD	1.1×10^{-3}
≥ 42	VD+ID+TPC	1.7×10^{-3}
≤ 36	VD + FCB included	1.3×10^{-3}
25-30	FCB included	1.5×10^{-3}
<25	FCB included	2.7×10^{-3}

Table 4: Momentum measurement precision for 45.6 GeV/c muons.



THE ATLAS TRACKER (PROJECTED PERFORMANCE)

1) 2 LAYERS SILICON PIXELS ($r = 11.5 - 17.5$ cm)

→ MOSTLY FOR PATTERN RECOGNITION & RAD. HARDNESS

→ $\sigma_{r\phi} \simeq 15\ \mu m$ (PITCH = $50\ \mu m$)

2) 4 LAYERS SILICON STRIPS ($r = 30 - 60$ cm)

$\sigma_{r\phi} \simeq 25\ \mu m$ (PITCH = $85\ \mu m$)

$\sigma_{rz} \simeq 800\ \mu m$ ($\theta_{STEREO} = 2$[illegible]$^\circ$)

3) 35 LAYERS OF STRAWS ($r = 63 - 107$ cm)

INTER STRAW REGION FILLED WITH TRANSITION RADIATOR (ELECTRON IDENTIFICATION)

$\sigma_{r\phi} = 150\ \mu m$ / STRAW (7 mm DIAMETER STRAWS)

ALSO GIVES MANY LAYERS OF $\simeq$ CONTINUOUS TRACKING HITS ⇒ "IMPROVED" PATTERN RECOGNITION.

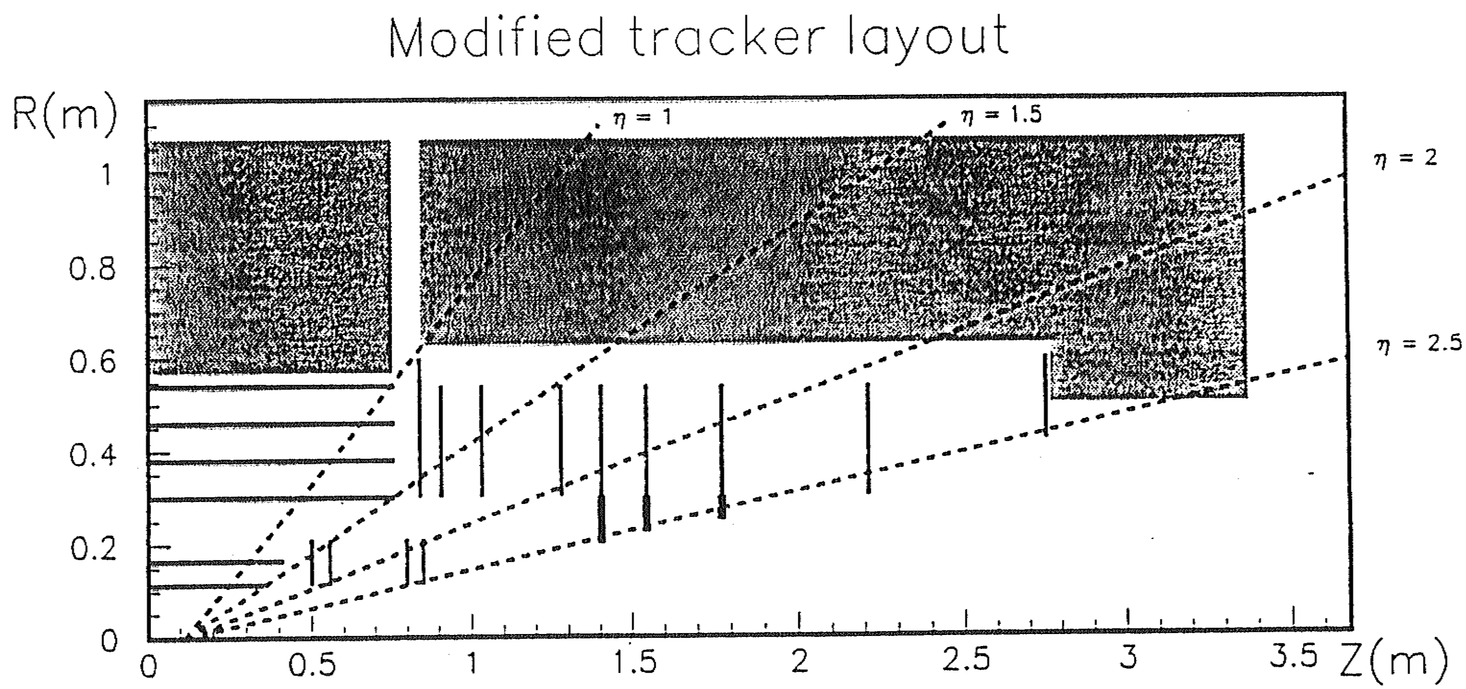
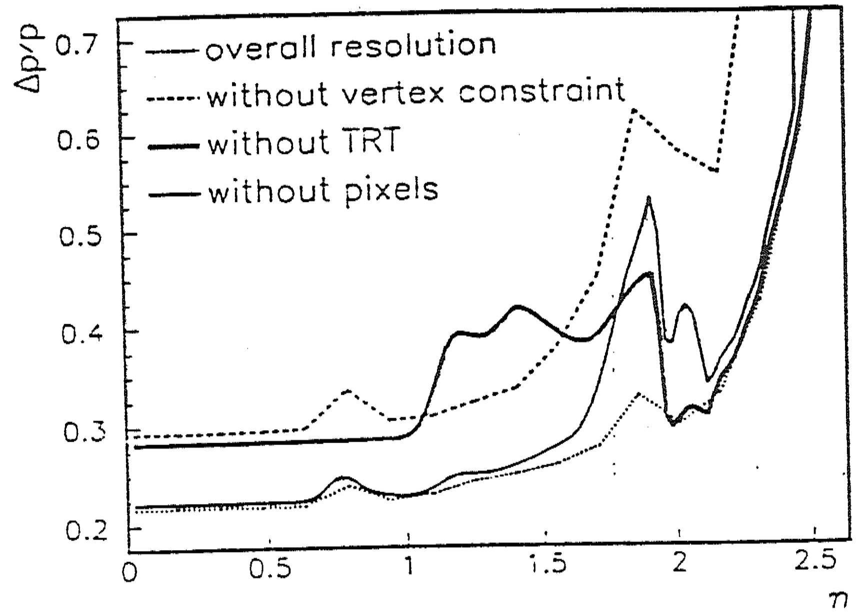


Figure 3.23: Conceptual layout of the silicon option for the forward precision tracking. Thin lines represent silicon detectors, while thicker lines represent GaAs detectors.

RESULTS (FROM SIMULATIONS)



$\frac{\sigma_{P_t}}{P_t} = 0.04\% P_t$

≥3x BETTER THAN CDF

Figure 3.35: Robustness of the momentum resolution versus η for muons of $p_T = 500$ GeV

Table 3.14: Parametrized impact-parameter resolution of the ATLAS inner detector for the barrel part of the various vertexing layouts described in the text. The resolutions are given as functions of p_T in GeV and of the polar angle, θ.

Vertex detector	σ_{ip} (μm)	σ_z (μm)
High luminosity	$27 \oplus \frac{220}{p_T\sqrt{\sin\theta}}$	$130 \oplus \frac{240}{p_T\sqrt{\sin\theta}}$
Binary pixels	$18 \oplus \frac{61}{p_T\sqrt{\sin\theta}}$	$84 \oplus \frac{130}{p_T\sqrt{\sin\theta^3}}$
Analog pixels	$12 \oplus \frac{52}{p_T\sqrt{\sin\theta}}$	$52 \oplus \frac{79}{p_T\sqrt{\sin\theta^3}}$
Micro-strips	$13 \oplus \frac{62}{p_T\sqrt{\sin\theta}}$	$39 \oplus \frac{90}{p_T\sqrt{\sin\theta^3}}$