Tracking Detectors

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Basic Tracking Concepts

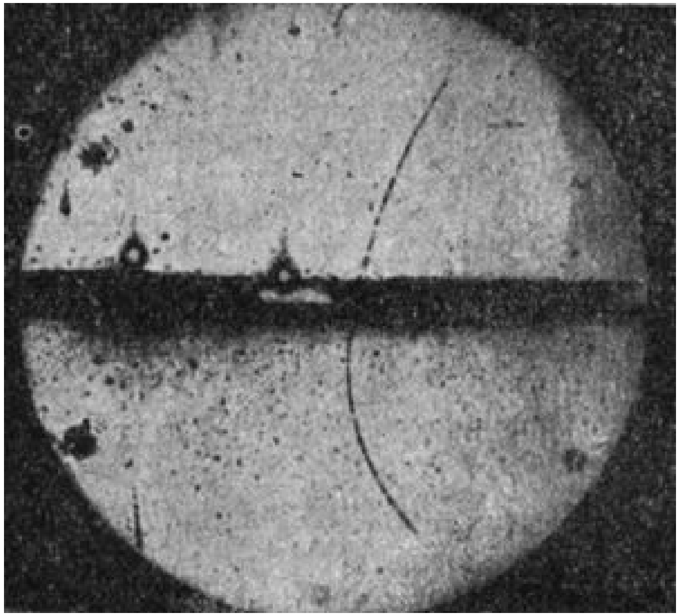
- Moving object (animal) disturbs the material

→ A track ←

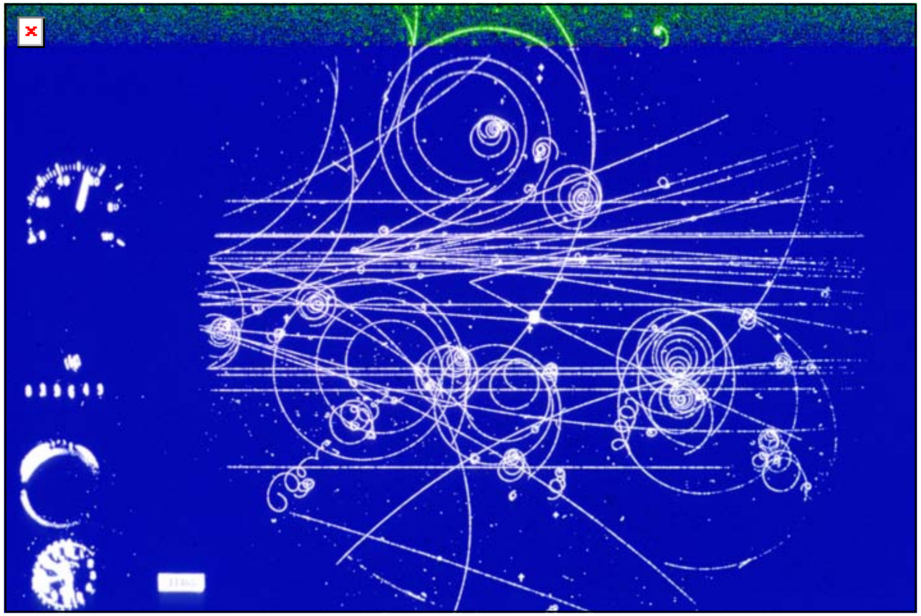
- Keen observers can learn
  - Identity
    - What made the track?
  - Position
    - Where did it go through?
  - Direction
    - Which way did it go?
  - Velocity
    - How fast was it moving?

Charged Particles

- Charged particles leave tracks as they penetrate material



Discovery of the positron
Anderson, 1932

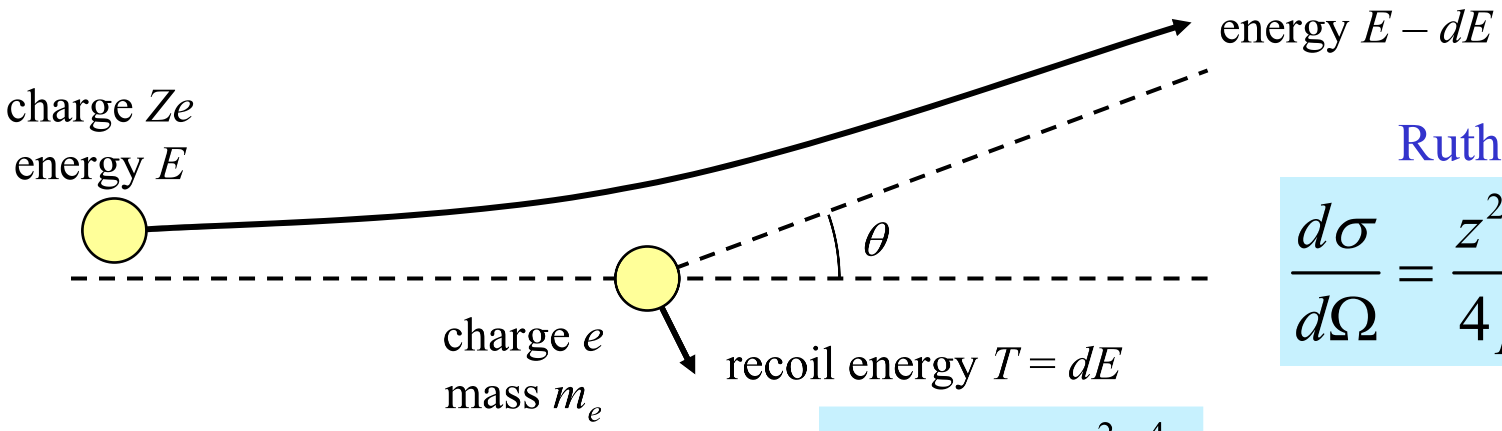


16 GeV π^- beam entering a liquid-H_2 bubble chamber at CERN, circa 1970

- "Footprint" in this case is excitation/ionization of the detector material by the incoming particle's electric charge

Coulomb Scattering

- Incoming particle scatters off an electron in the detector



Rutherford

$$\frac{d\sigma}{d\Omega} = \frac{z^2 e^4}{4pv} \csc^4 \frac{\theta}{2}$$

  - Transform variable to T ➔ $$\frac{d\sigma}{dT} = \frac{2\pi z^2 e^4}{mc^2 \beta T^2}$$

- Integrate above minimum energy (for ionization/excitation) and multiply by the electron density
  - See P. Fisher's lecture from NEPPSR'03

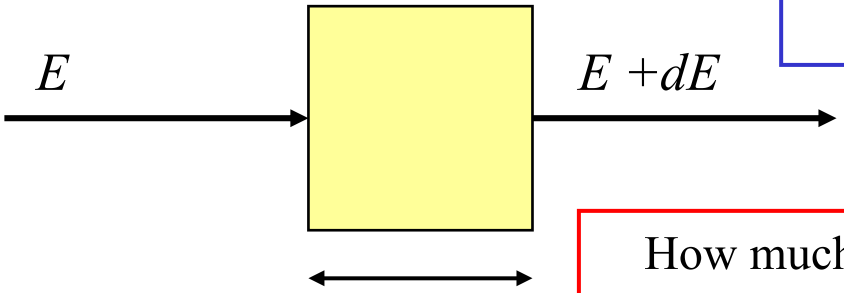
Bethe-Bloch Formula

- Average rate of energy loss [in MeV $\mathrm{g}^{-1}\mathrm{cm}^2$]

$$\frac{}{dx} = -Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

$$K = 4\pi N_A r_e^2 m_e c^2$$
$$= 0.307\,\mathrm{MeV g^{-1} cm^2}$$

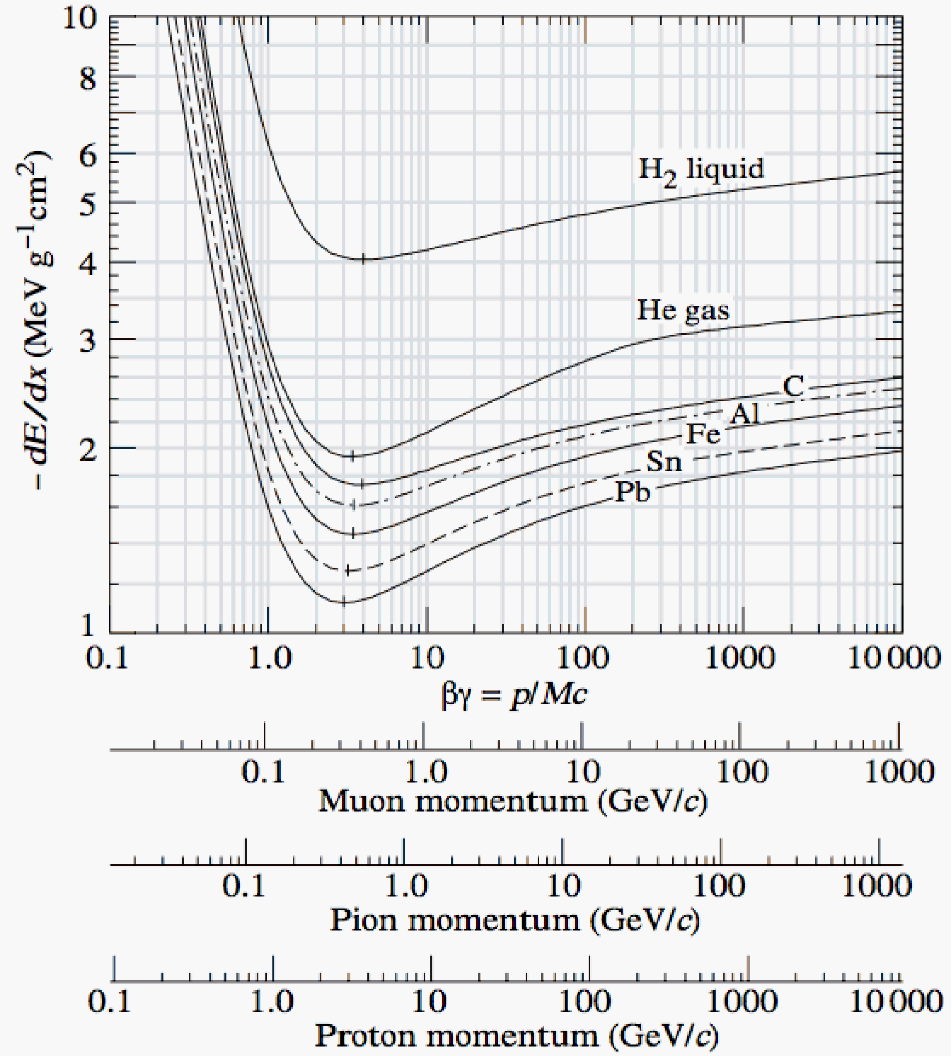
  - I = mean ionization/excitation energy [MeV]
  - δ = density effect correction (material dependent)
- What's the funny unit?



How much energy is lost?
$-dE$ [MeV]

How much material is traversed?
dx = thickness [cm] × density [$\mathrm{g/cm^3}$]

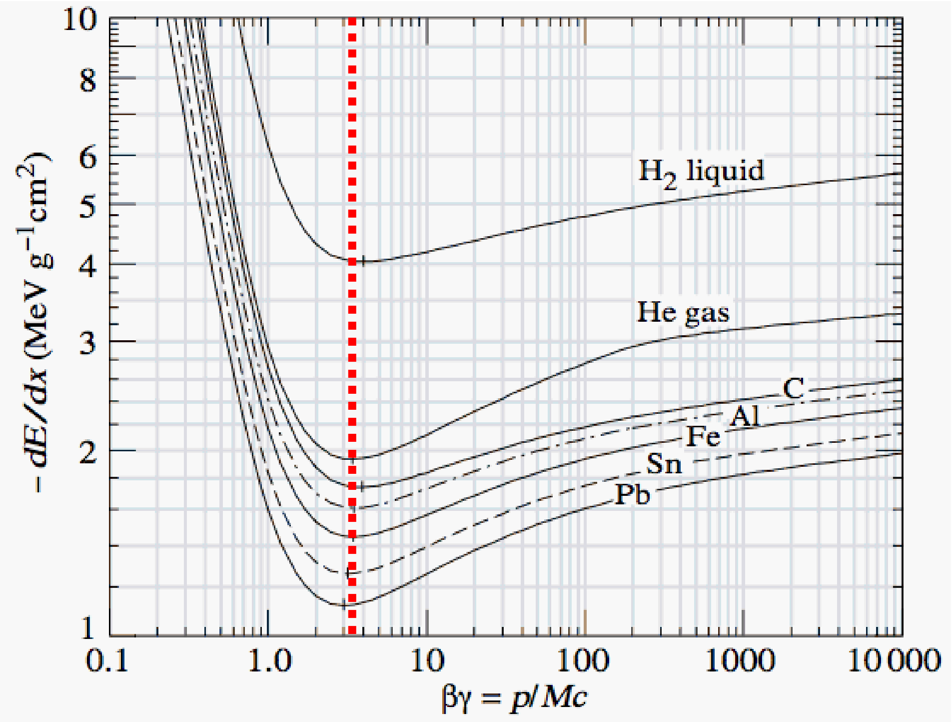
Bethe-Bloch Formula



$$\frac{dE}{dx} = -Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\gamma^2\beta^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

- *dE/dx* depends only on β (and z) of the particle
- At low β, $dE/dx \propto 1/\beta^2$
  - Just kinematics
- Minimum at $\beta\gamma \sim 4$
- At high β, *dE/dx* grows slowly
  - Relavistic enhancement of the transverse **E** field
- At very high β, *dE/dx* saturates
  - Shielding effect

Minimum Ionizing Particles



Gas	Primary [/cm]	Total [/cm]
He	5	16
CO_2	35	107
C_2H_6	43	113

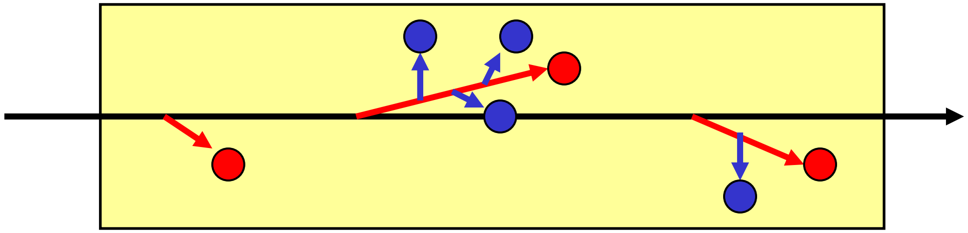
- Particles with $\beta \sim 4$ are called minimum-ionizing particles (mips)
- A mip loses 1–2 MeV for each g/cm^2 of material
  - Except Hydrogen
- Density of ionization is

$$\frac{(dE/dx)_{\text{mip}}}{I}$$

  - Determines minimal detector thickness

Primary and Secondary Ionization

- An electron scattered by a charged particle may have enough energy to ionize more atoms



3 primary + 4 secondary ionizations

  - Signal amplitude is (usually) determined by the total ionization
  - Detection efficiency is (often) determined by the primary ionization

Gas	Primary [/cm]	Total [/cm]
He	5	16
CO_2	35	107
C_2H_6	43	113

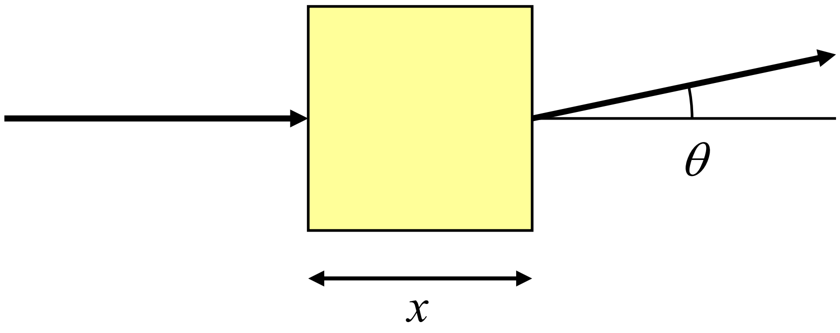
Ex: 1 cm of helium produce on average 5 primary electrons per mip.

$$\varepsilon = 1 - e^{-5} = 0.993$$

A realistic detector needs to be thicker.

Multiple Scattering

- Particles passing material also change direction



θ is random and almost Gaussian

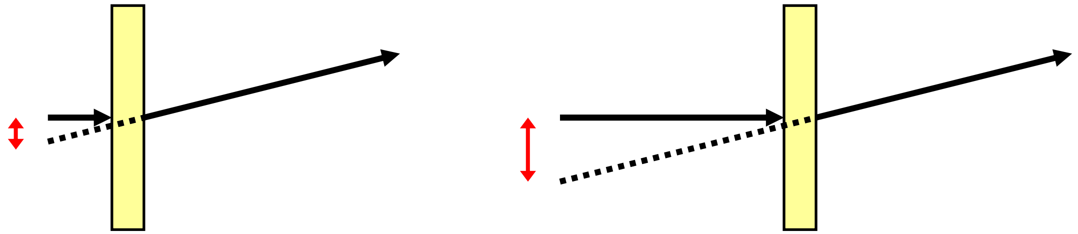
$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{13.6\,\text{MeV}}{\beta cp} z\sqrt{x/X_0}\left[1 + 0.038\ln(x/X_0)\right]$$

- $\theta \propto 1/p$ for relativistic particles
- Good tracking detector should be light (small x/X_0) to minimize multiple scattering

Matrial	Radiation length X_0 [g/cm^2]	[cm]
H_2 gas	61.28	731000
H_2 liguid		866
C	42.70	18.8
Si	21.82	9.36
Pb	6.37	0.56
C_2H_6	45.47	34035

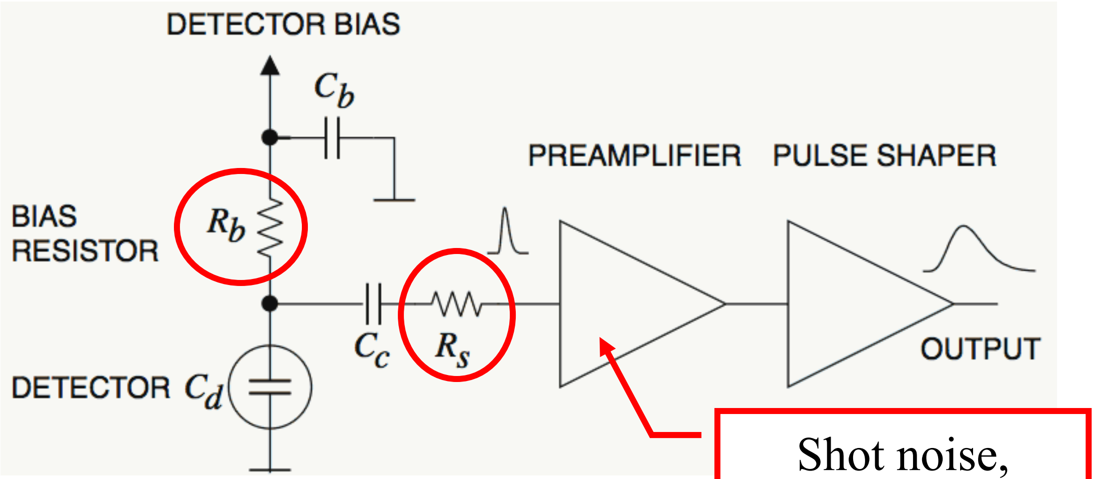
Optimizing Detector Material

- A good detector must be
  - thick enough to produce sufficient signal
  - thin enough to keep the multiple scattering small
- Optimization depends on many factors:
  - How many electrons do we need to detect signal over noise?
    - It may be 1, or 10000, depending on the technology
  - What is the momentum of the particle we want to measure?
    - LHC detectors can be thicker than BABAR
  - How far is the detector from the interaction point?



Readout Electronics

- Noise of a well-designed detector is calculable
  - Increases with C_d
  - Increases with the bandwidth (speed) of the readout



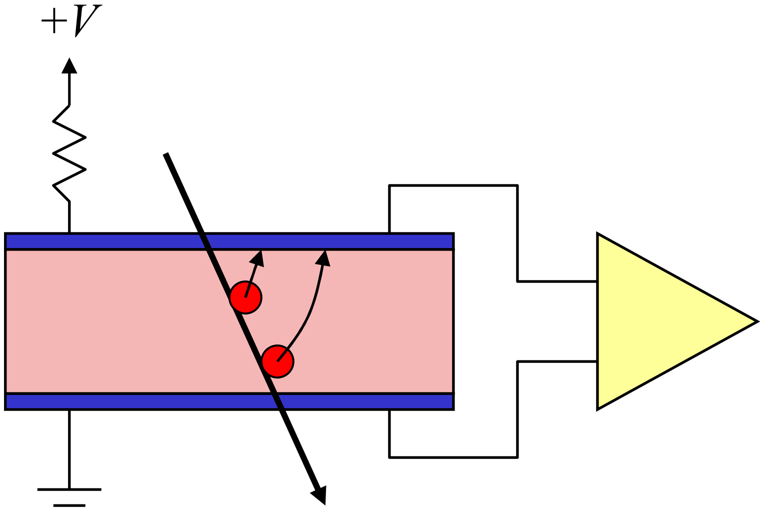
Shot noise, feedback resistor

- Equivalent noise charge Q_n = size of the signal that would give $S/N = 1$
  - Typically 1000–2000 electrons for fast readout (drift chambers)
  - Slow readout (liguid Ar detectors) can reach 150 electrons

  - More about electronics by John later today

Silicon Detectors

- Imagine a piece of pure silicon in a capacitor-like structure



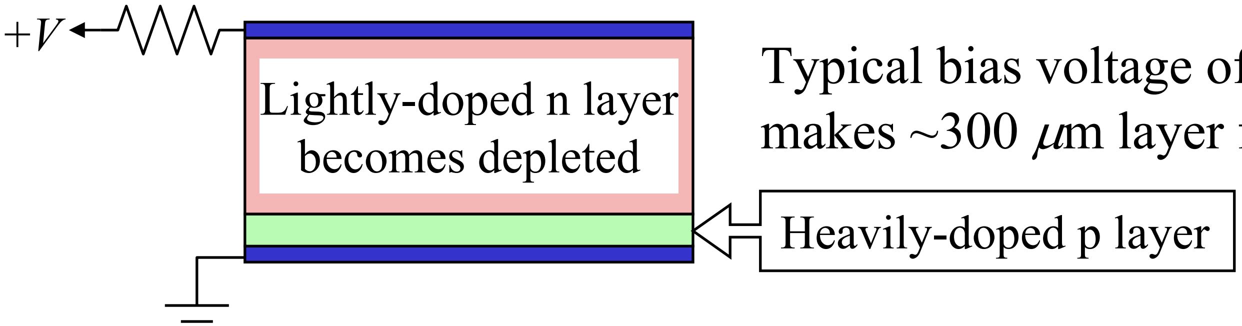
$dE/dx_{\mathrm{min}} = 1.664\ \mathrm{MeVg^{-1}cm^2}$
Density = 2.33 g/cm^3
Excitation energy = 3.6 eV

⇒ 10^6 electron-hole pair/cm

Assume Q_n = 2000 electron and require $S/N > 10$

⇒ Thickness > 200 μm

- Realistic silicon detector is a reverse-biased p-n diode



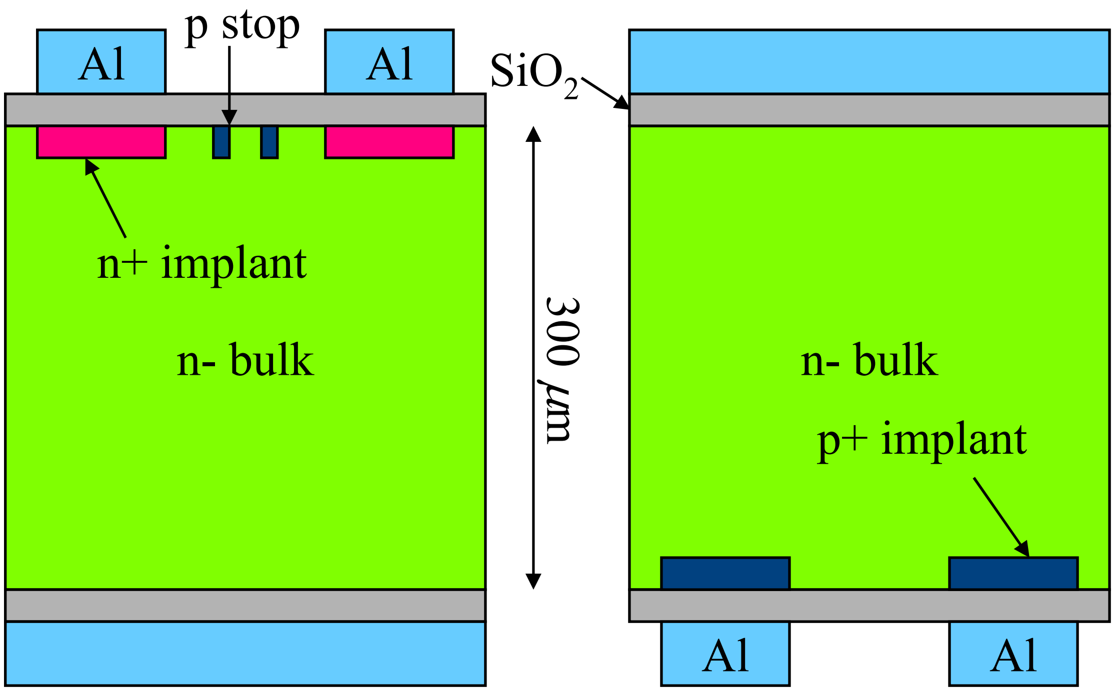
Lightly-doped n layer becomes depleted

Heavily-doped p layer

Typical bias voltage of 100–200 V makes ~300 μm layer fully depleted

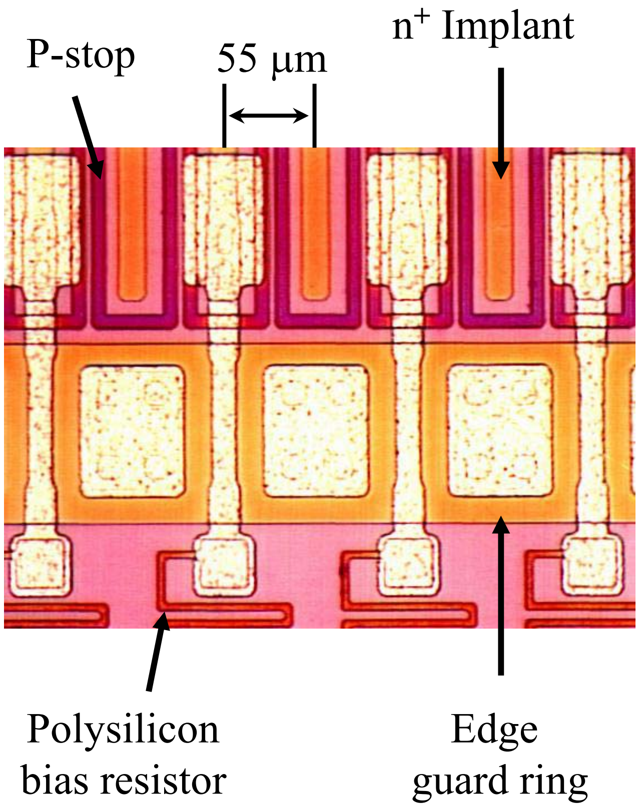
BABAR Silicon Detector

- Double-sided detector with AC-coupled readout



X view

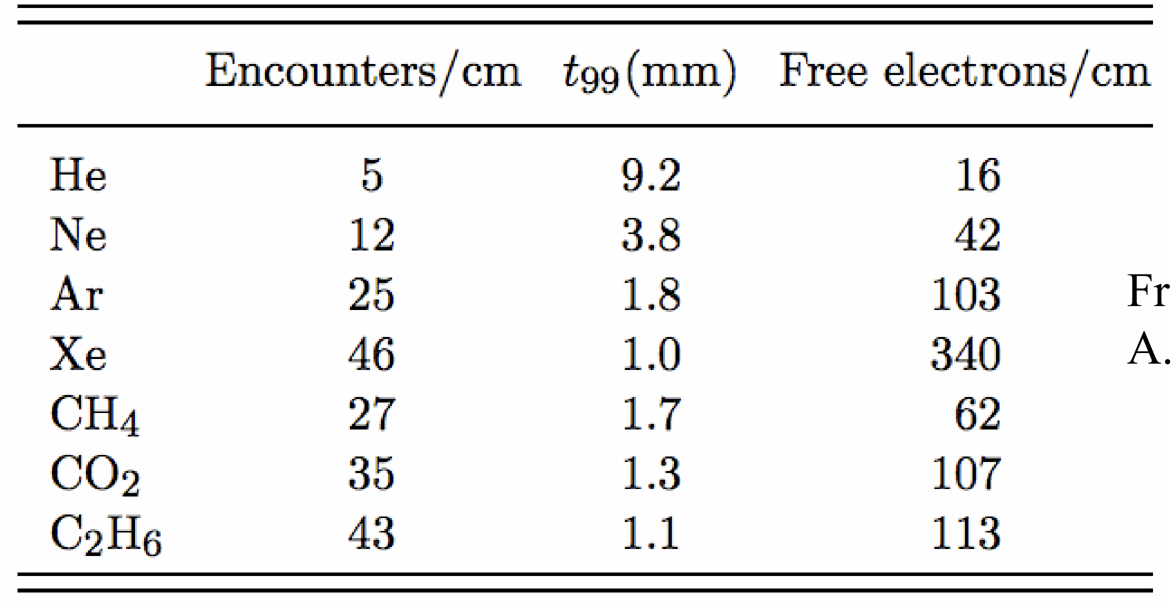
Y view



- Aluminum strips run X/Y directions on both surfaces

Wire Chambers

- Gas-based detectors are better suited in covering large volume
  - Smaller cost + less multiple scattering
- Ionization < 100 electrons/cm ➔ Too small for detection
  - Need some form of amplification before electronics

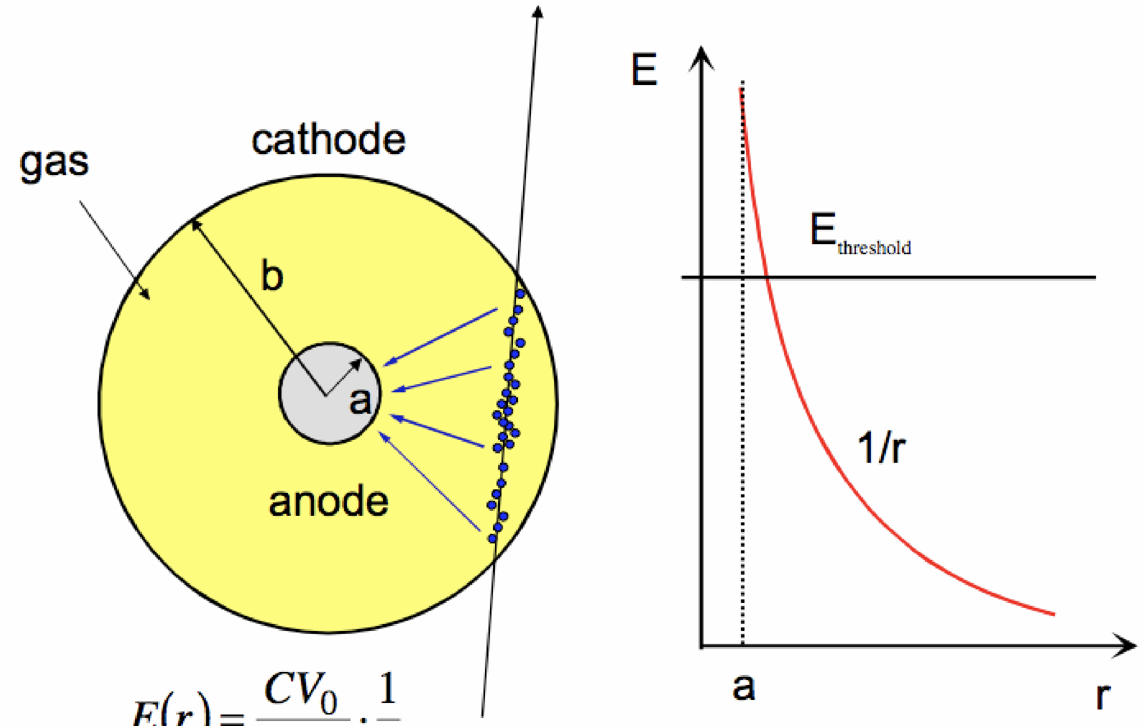


	Encounters/cm	t_{99}(mm)	Free electrons/cm
He	5	9.2	16
Ne	12	3.8	42
Ar	25	1.8	103
Xe	46	1.0	340
CH_4	27	1.7	62
CO_2	35	1.3	107
C_2H_6	43	1.1	113

From PDG
A. Cattai and G. Rolandi

Gas Amplification

- String a thin wire (anode) in the middle of a cylinder (cathode)



$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

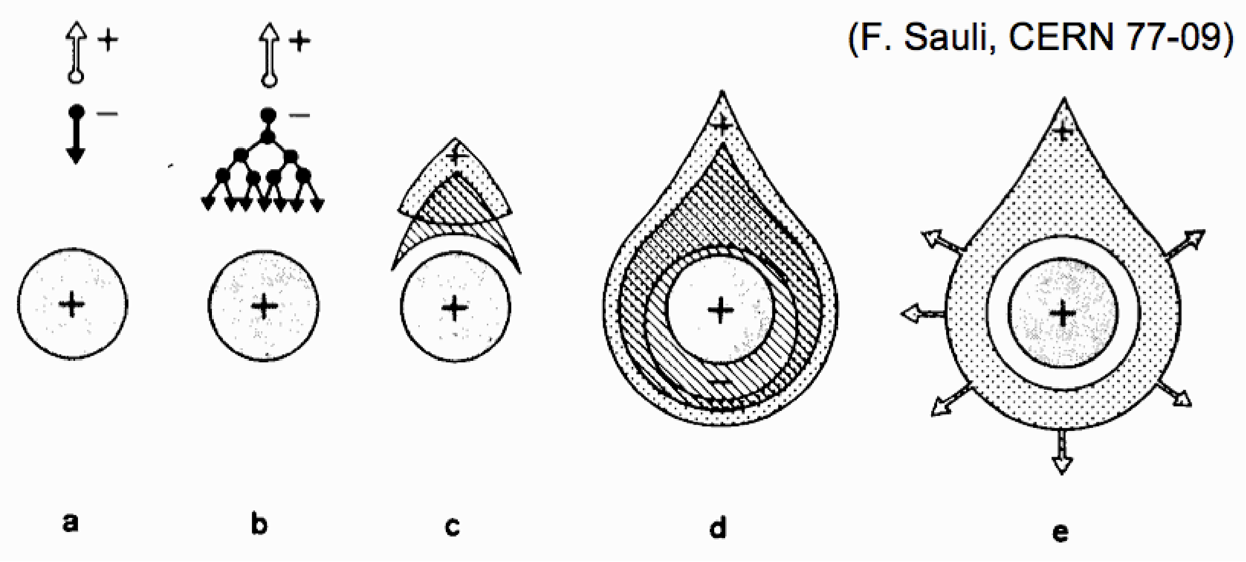
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

C = capacitance / unit length

- Apply high voltage
- Electrons drift toward the anode, bumping into gas molecules
- Near the anode, **E** becomes large enough to cause secondary ionization
- Number of electrons doubles at every collision

Avalanche Formation

- Avalanche forms within a few wire radii



(F. Sauli, CERN 77-09)

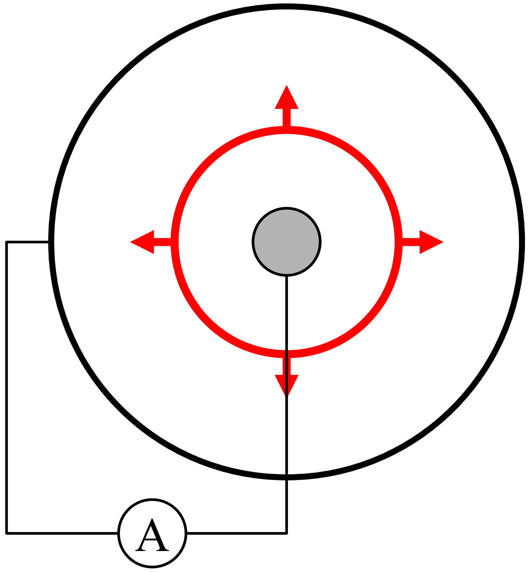
  - Electrons arrive at the anode quickly (< 1ns spread)
  - Positive ions drift slowly outward
    - Current seen by the amplifier is dominated by this movement

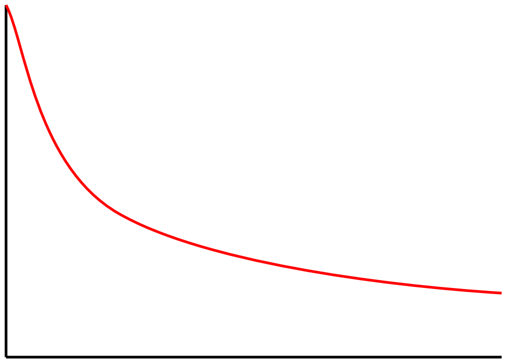
Signal Current

- Assuming that positive ion velocity is proportional to the E field, one can calculate the signal current that flows between the anode and the cathode

$$I(t) \propto \frac{1}{t+t_0}$$

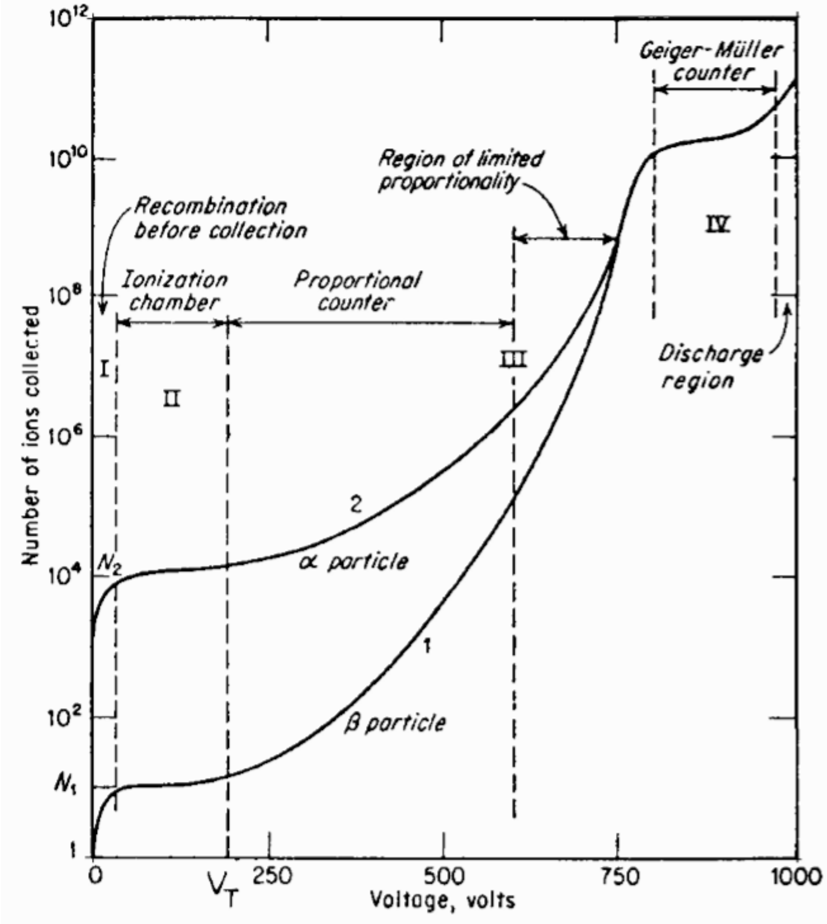
- This “1/*t*” signal has a very long tail
  - Only a small fraction (~1/5) of the total charge is available within useful time window (~100 ns)
  - Electronics must contain differentiation to remove the tail





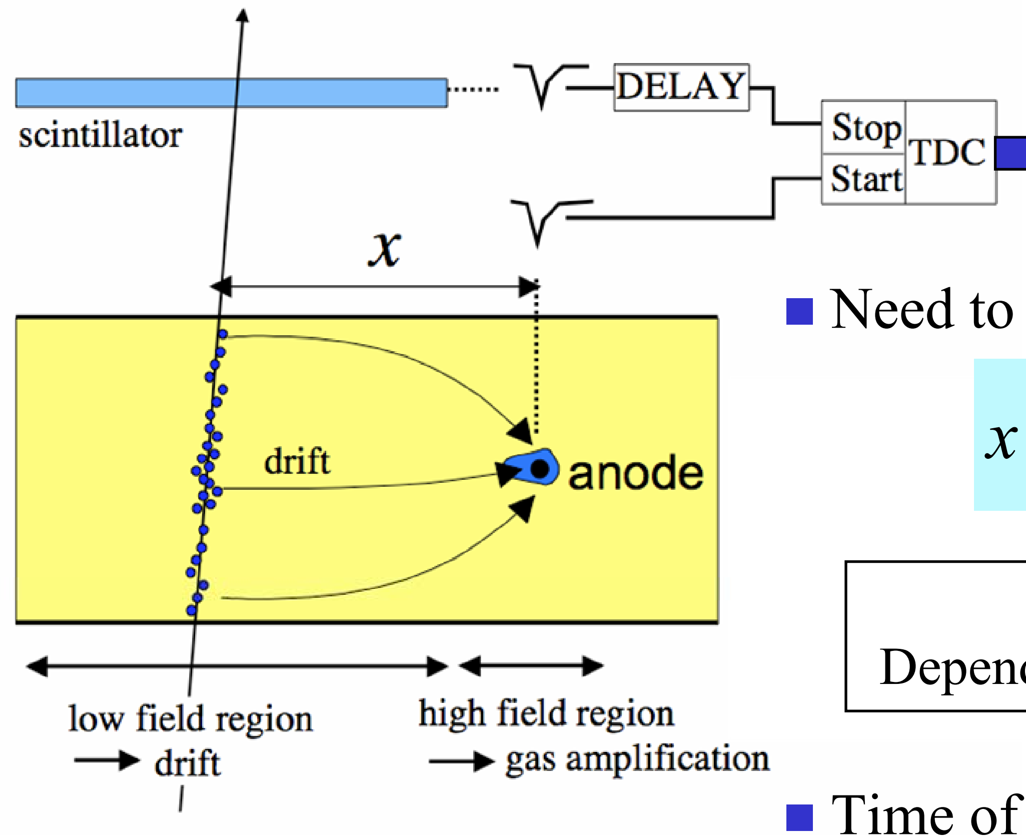
Gas Gain

- Gas gain increases with HV up to 10^5–10^6
  - With Q_n = 2000 electrons and a factor 1/5 loss due to the $1/t$ tail, gain = 10^5 can detect a single-electron signal
- What limits the gas gain?
  - Recombination of electron-ion produces photons, which hit the cathode walls and kick out photo-electrons
    ➔ Continuous discharge
  - Hydrocarbon is often added to suppress this effect



Drift Chambers

- Track-anode distance can be measured by the drift time



- Need to know the x-vs-t relation

$$x = \int_0^t v_D(t')dt'$$

Drift velocity
Depends on the local E field

- Time of the first electron is most useful

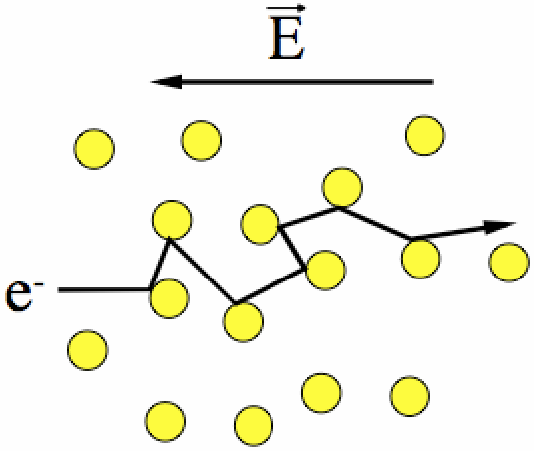
Drift Velocity

- Simple stop-and-go model predicts

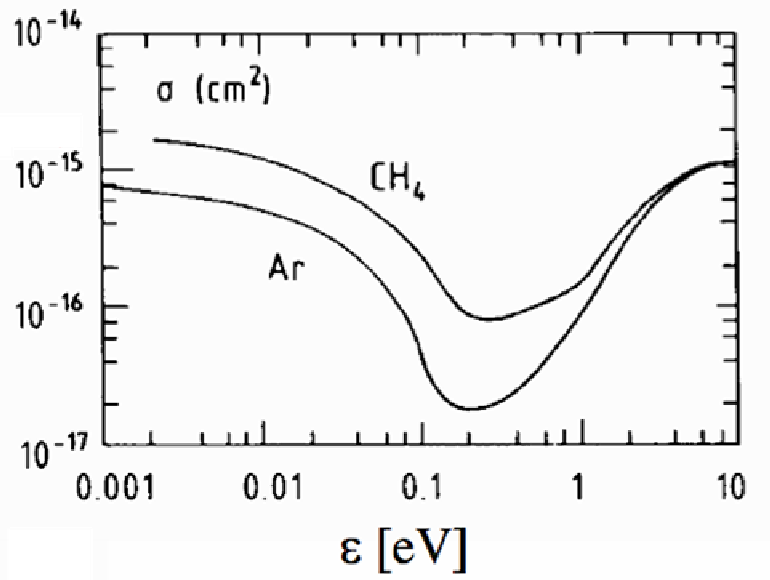
$$\vec{v}_D = \frac{e\tau}{m}\vec{E} = \mu\vec{E}$$

τ = mean time between collisions

  - μ = mobility (constant)
  - This works only if the collision cross section σ is a constant

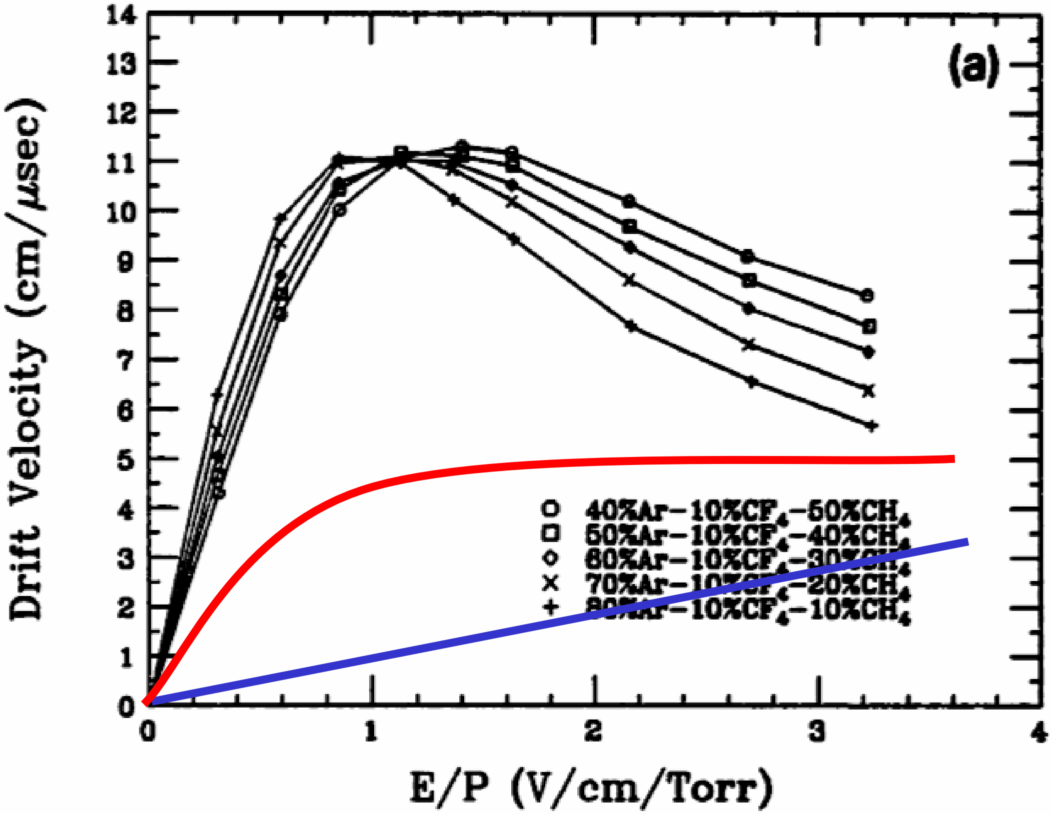


- For most gases, σ is strongly dependent on the energy ε
  - v_D tends to saturate
  - It must be measured for each gas
  - *c.f.* μ is constant for drift of positive ions



Drift Velocity

- Example of v_D for Ar-CF_4-CH_4 mixtures
  - “Fast” gas
- Typical gas mixtures have $v_D \sim 5$ cm/μs
  - e.g. Ar(50)-C_2H_6(50)
  - Saturation makes the *x*-*t* relation linear
- “Slow” gas mixtures have $v_D \propto E$
  - e.g. CO_2(92)-C_2H_6(8)



T. Yamashita *et al.*, NIM A317 (1992) 213

Spatial Resolution

- Typical resolution of a drift chamber is 50–200 μm
  - Diffusion: random fluctuation of the electron drift path

    $$\sigma_x(t) = \sqrt{2Dt} \qquad D = \text{diffusion coefficient}$$

    - Smaller cells help
    - “Slow gas” has small D

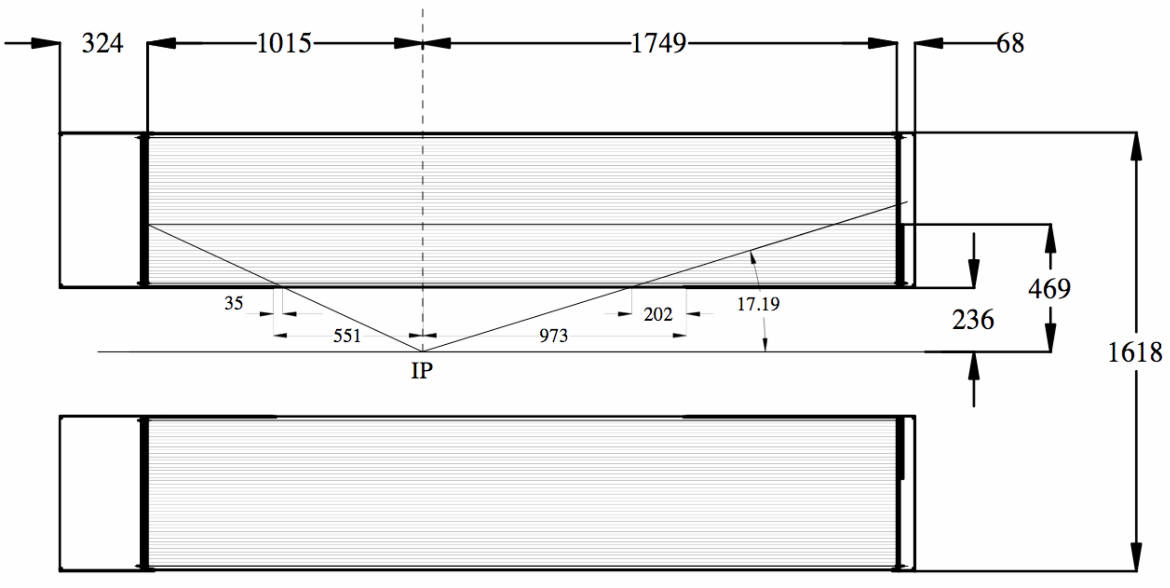
    $\left.\begin{array}{l}\\ \\ \end{array}\right\}$ Micro vertex chambers (e.g. Mark-II)
  - Primary ionization statistics
    - Where is the first-arriving electron?
  - Electronics
    - How many electrons are needed to register a hit?
    - Time resolution (analog and digital)
  - Calibration of the x-t relation
  - Alignment

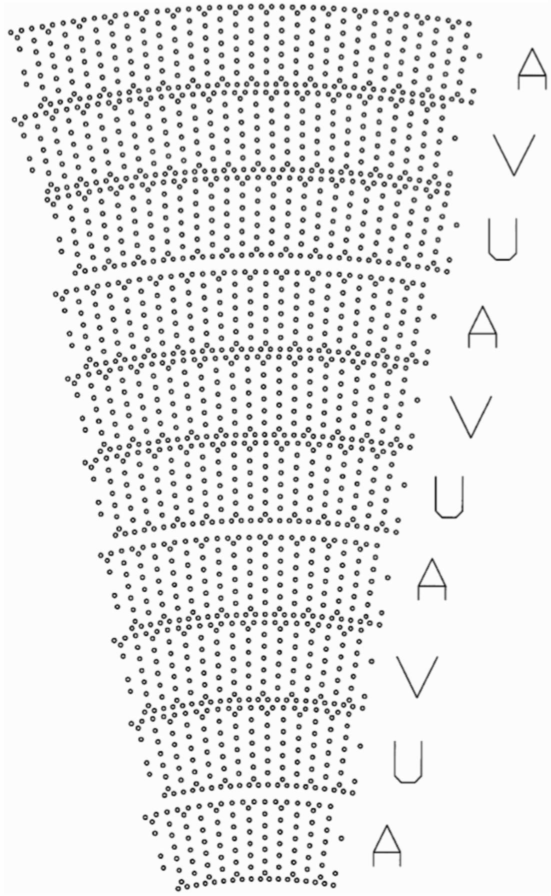
Other Performance Issues

- *dE*/*dx* resolution – particle identification
  - Total ionization statistics, # of sampling per track, noise
  - 4% for OPAL jet chamber (159 samples)
  - 7% for BABAR drift chamber (40 samples)
- Deadtime – how quickly it can respond to the next event
  - Maximum drift time, pulse shaping, readout time
  - Typically a few 100 ns to several microseconds
- Rate tolerance – how many hits/cell/second it can handle
  - Ion drift time, signal pile up, HV power supply
  - Typically 1–100 kHz per anode
  - Also related: radiation damage of the detector

Design Exercise

- Let’s see how a real drift chamber has been designed
  - Example: BABAR drift chamber





Requirements

- Cover as much solid angle as possible around the beams
  - Cylindrical geometry
- Inner and outer radii limited by other elements
  - Inner radius ~20 cm: support pipe for the beam magnets
  - Out radius ~80 cm: calorimeter (*very* expensive to make larger)
- Particles come from decays of *B* mesons
  - Maximum p_t ~2.6 GeV/*c*
  - Resolution goal: $\sigma(p_t)/p_t = 0.3\%$ for 1 GeV/*c*
  - Soft particles important ➔ Minimize multiple scattering!
  - Separating π and K important ➔ dE/dx resolution 7%
- Good (not extreme) rate tolerance
  - Expect 500 k tracks/sec to enter the chamber

Momentum Resolution

- In a B field, p_t of a track is given by

$$p_T = 0.3B\rho$$

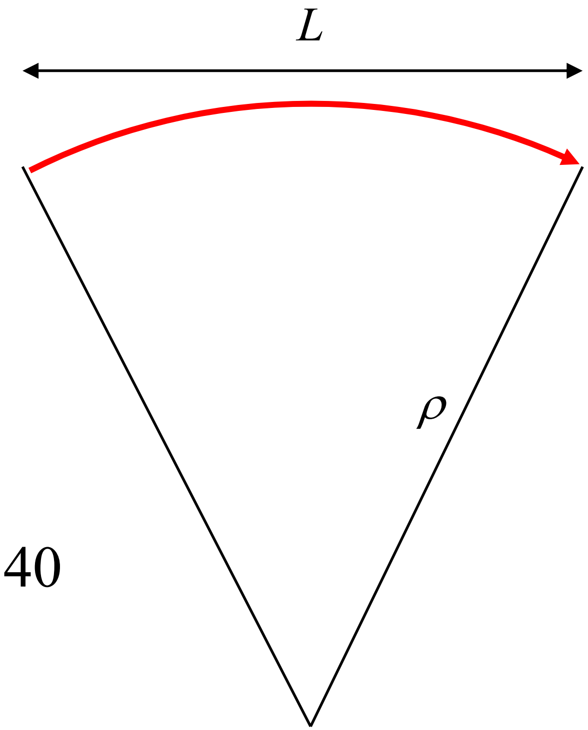
  - If N measurements are made along a length of L to determine the curvature

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

  - Given L = 60 cm, a realistic value of N is 40
  - To achieve 0.3% resolution for 1 GeV/c

$$\frac{\sigma_x}{B} = 80\ \mu\text{m/T}$$

  - We can achieve this with σ_x = 120 μm and B = 1.5 T

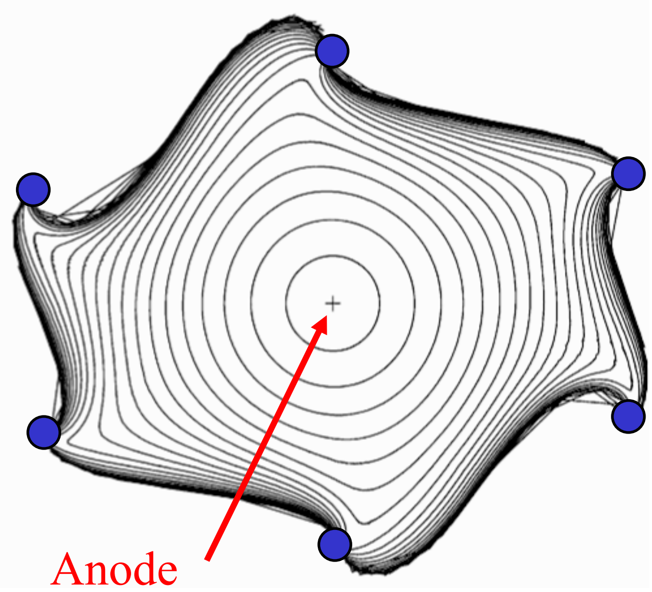


Multiple Scattering

- Leading order: $\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{L/X_0}$
  - Impact on p_T measurement $\sigma(p_T) = p_T \theta_0 = 0.0136 \sqrt{L/X_0}$
  - For an argon-based gas, $X_0(\mathrm{Ar}) = 110$ m, $L = 0.6$ m
    ➔ $\sigma(p_T) = 1$ MeV/c ➔ Dominant error for $p_T < 580$ MeV/c
  - We need a lighter gas!
- He(80)-C_2H_6(20) works better
  - $X_0 = 594$ m ➔ $\sigma(p_T) = 0.4$ MeV/c
- We also need light materials for the structure
  - Inner wall is 1 mm beryllium (0.28%X_0)
  - Then there are the wires

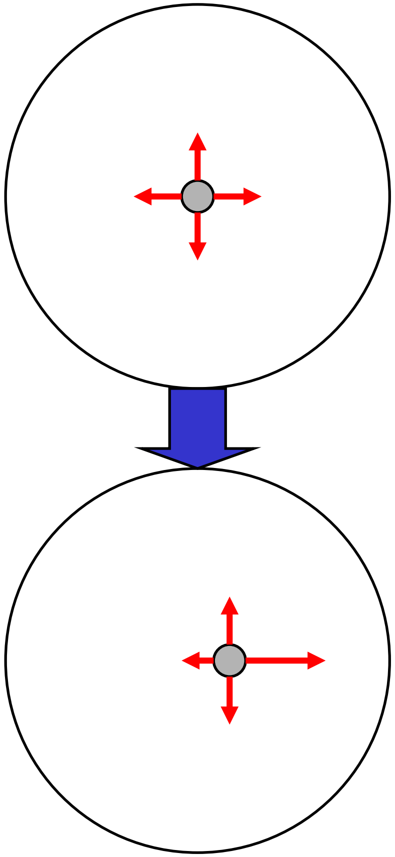
Wires

- Anode wires must be thin enough to generate high E field, yet strong enough to hold the tension
  - Pretty much only choice: 20 μm-thick Au-plated W wire
  - Can hold ~60 grams
  - BABAR chamber strung with 25 g
- Cathode wires can be thicker
  - High surface field leads to rapid aging
  - Balance with material budget
  - BABAR used 120 μm-thick Au-plated Al wire
- Gas and wire add up to 0.3%X_0



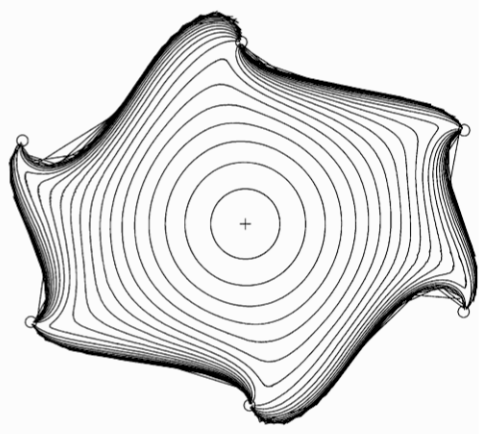
Wire Tension

- Anode wire are located at an unstable equilibrium due to electrostatic force
  - They start oscillating if the tension is too low
  - Use numerical simulation (e.g. Garfield) to calculate the derivative $d\mathbf{F}/d\mathbf{x}$
  - Apply sufficient tension to stabilize the wire
  - Cathode wire tension is often chosen so that the gravitational sag matches for all wires
- Simulation is also used to trace the electron drift and predict the chamber's performance

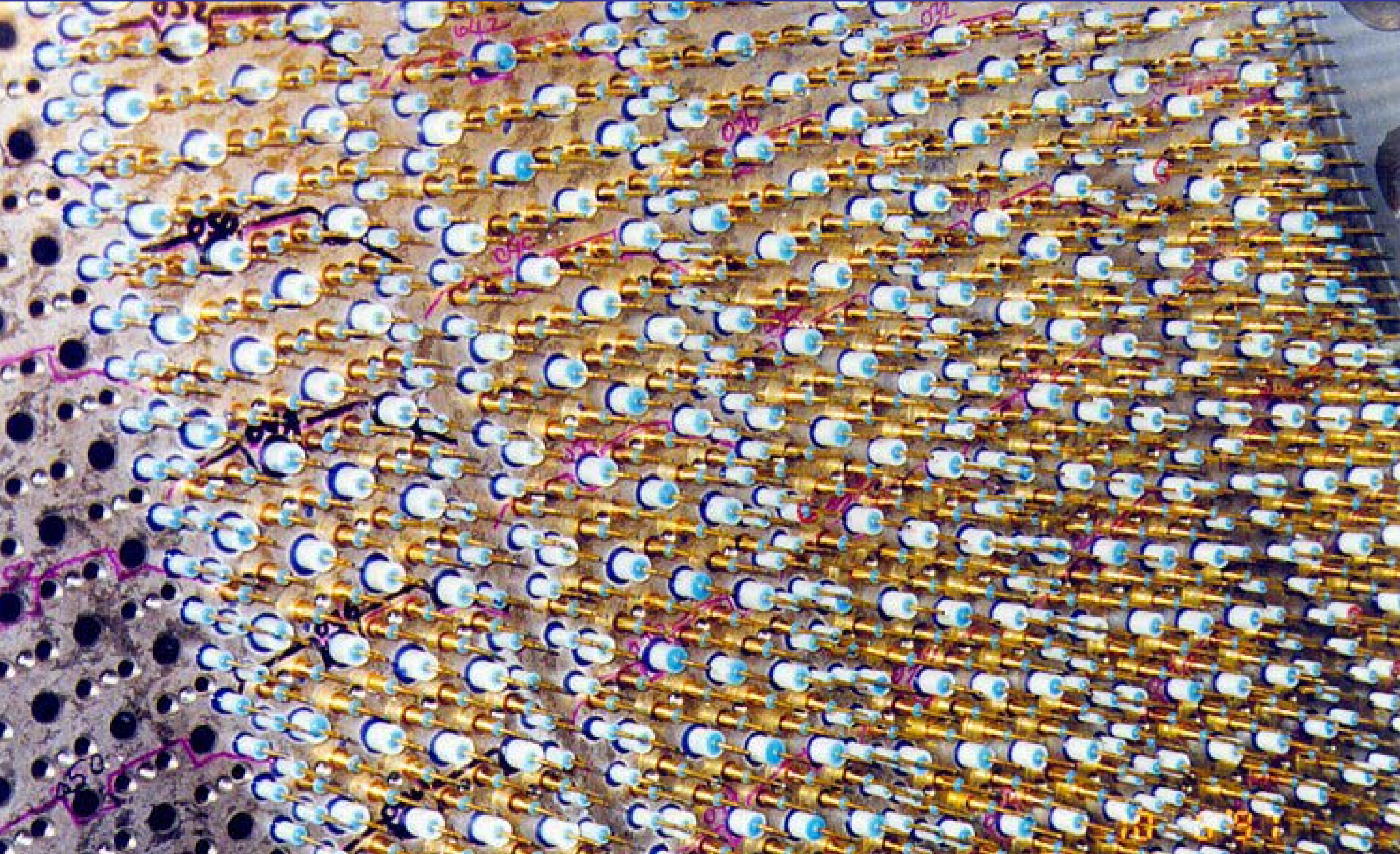


Cell Size

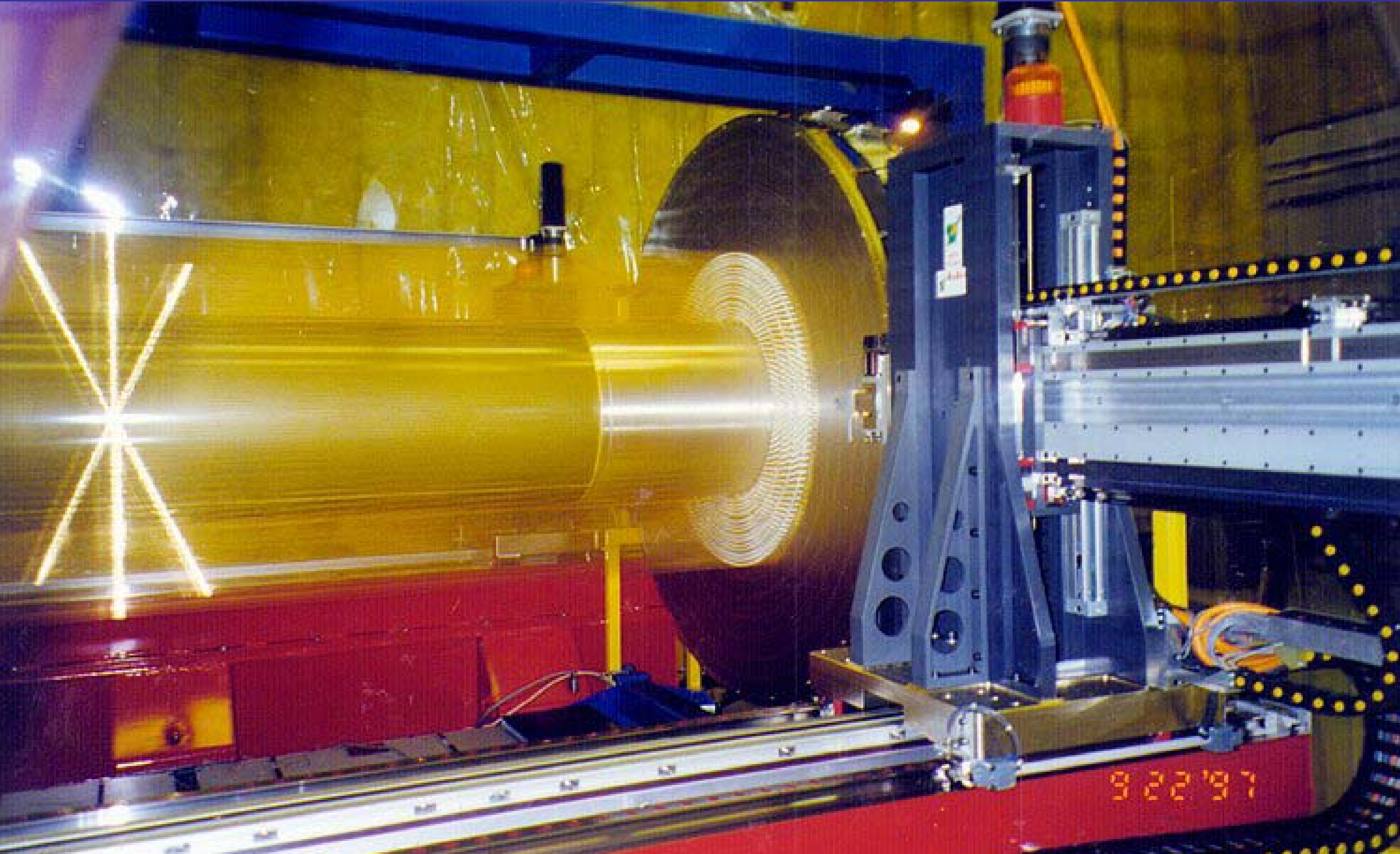
- Smaller cells are better for high rates
  - More anode wires to share the rate
  - Shorter drift time ➔ shorter deadtime
- Drawbacks are
  - More readout channels ➔ cost, data volume, power, heat
  - More wires ➔ material, mechanical stress, construction time
- Ultimate limit comes from electrostatic instability
  - Minimum cell size for given wire length
- BABAR chose a squashed hexagonal cells
  - 1.2 cm radial × 1.6 cm azimuthal
  - 96 cells in the innermost layer



End Plate Close Up



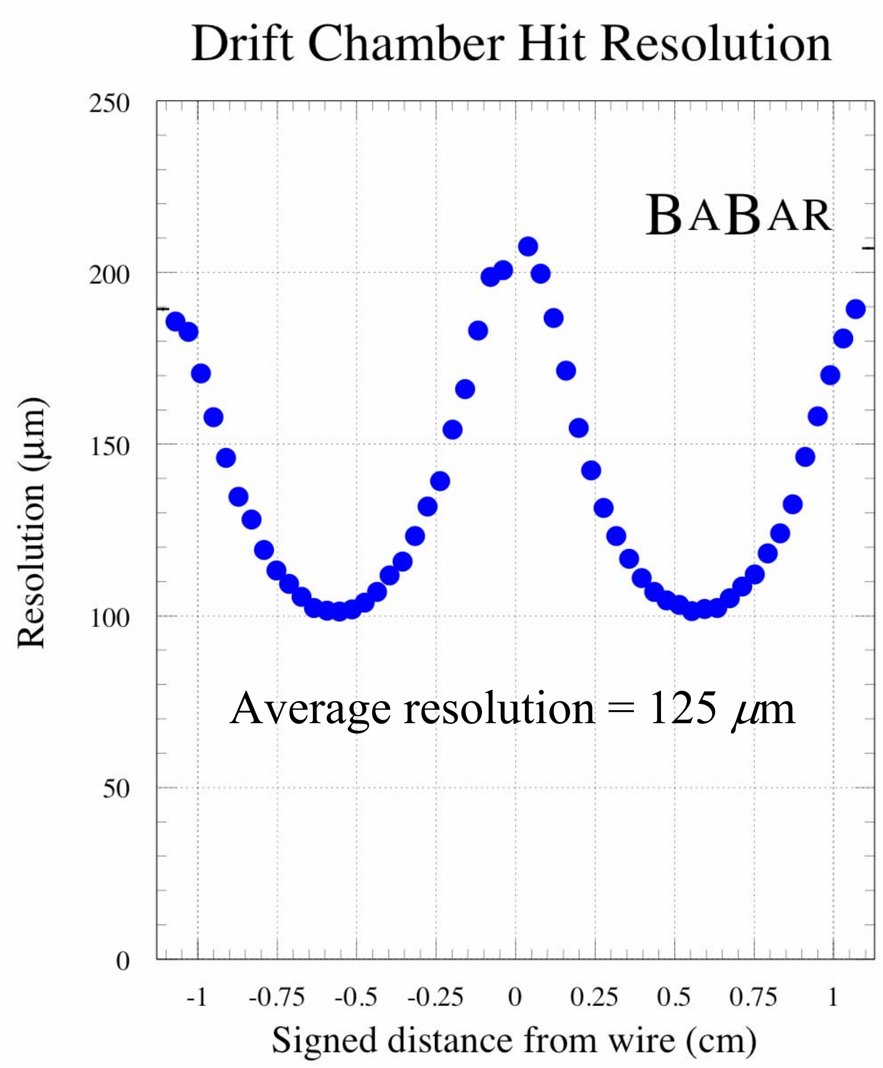
Wire Stringing In Progress

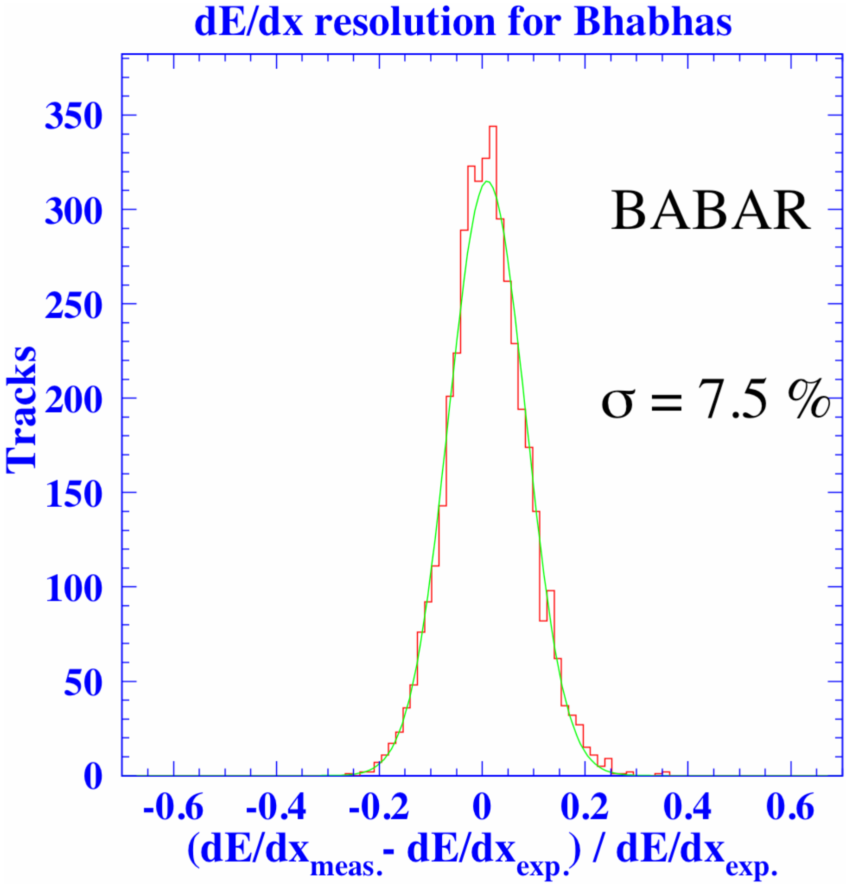


Gas Gain and Electronics

- With He(80)-C_2H_6(20), we expect 21 primary ionizations/cm
  - Simulation predicts ~80 μm resolution for leading electron
  - Threshold at 2–3 electrons should give 120 μm resolution
- Suppose we set the threshold at 10000 *e*, and 1/5 of the charge is available (1/*t* tail) ➔ Gas gain ~ 2×10^4
  - Easy to achieve stable operation at this gas gain
  - Want to keep it low to avoid aging
- Drift velocity is ~25 μm/ns
  - Time resolution must be <5 ns
  - Choose the lowest bandwidth compatible with this resolution
    - Simulation suggests 10–15 MHz

Actual Performance





Further Reading

- F. Sauli, *Principles of Operation of Multiwire Proportional and Drift Chambers*, CERN 77-09
- C. Joram, *Particle Detectors*, 2001 CERN Summer Student Lectures
- U. Becker, *Large Tracking Detectors*, NEPPSR-I, 2002
- A. Foland, *From Hits to Four-Vectors*, NEPPSR-IV, 2005