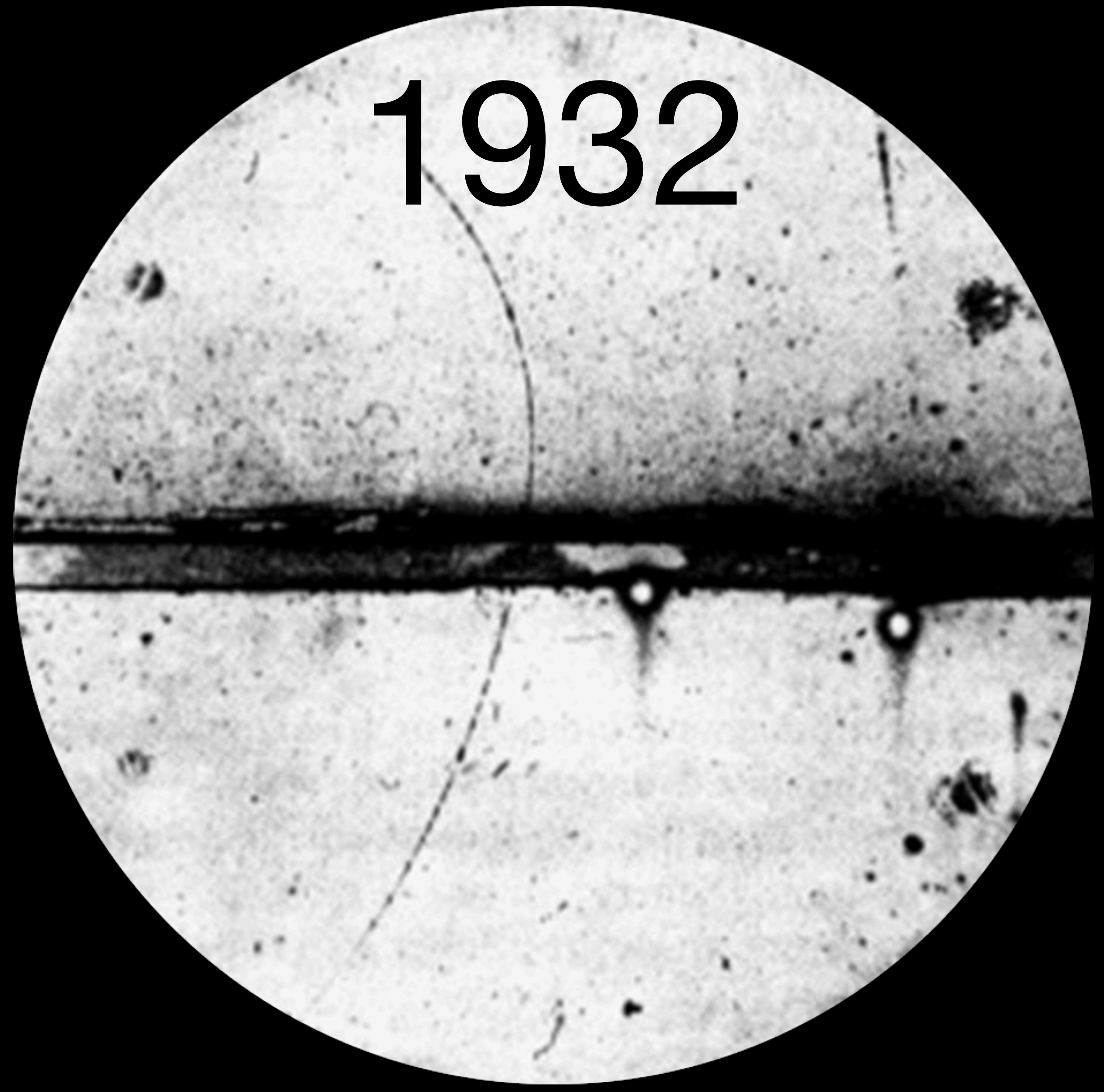
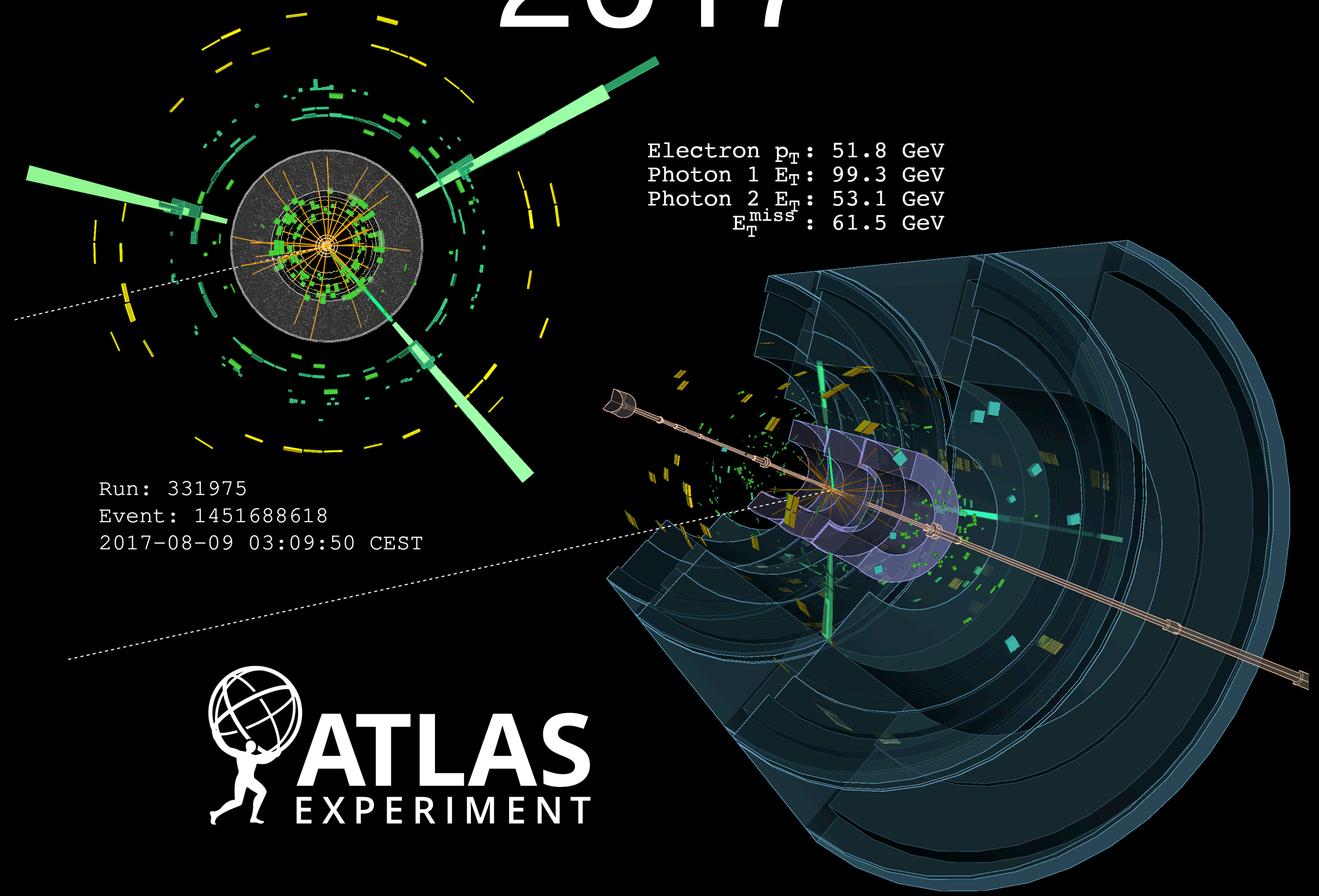
PHYS 7363 - Experimental Particle Detection and Detectors I



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we “see” subatomic particles, this course is for you!

2017



Detect Identify Measure

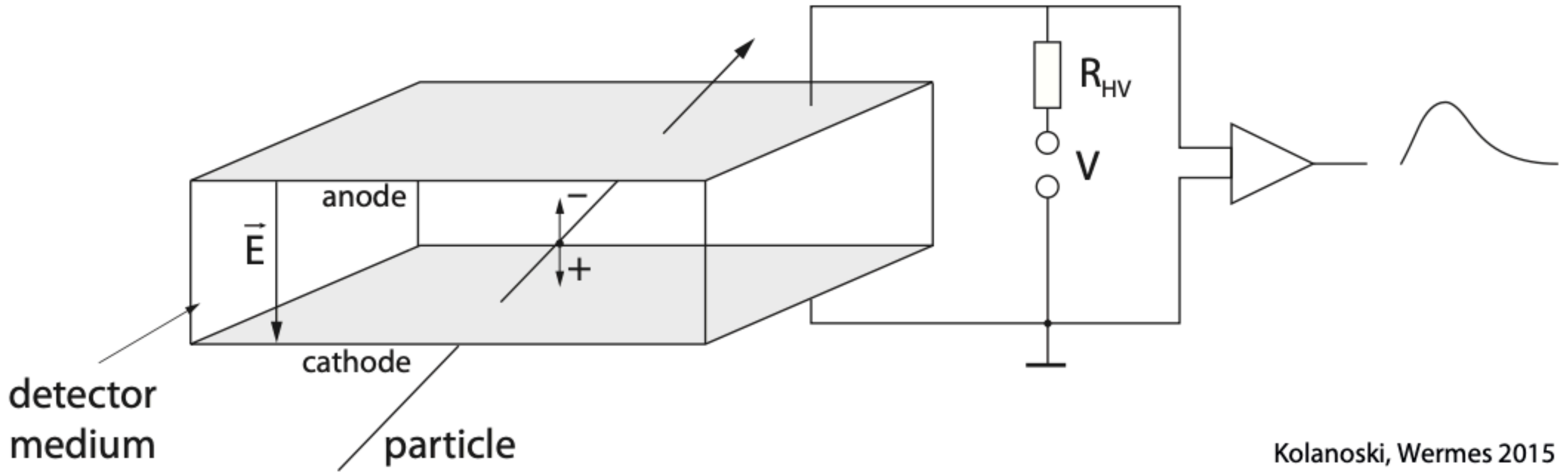
To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6 ✅ 1.5 hours	7	8 ✅ 1.5 hours	9	10	11	12
	13 ✅ 1.5 hours	14	15 ✅ 1.5 hours	16	17 ✅	18	19
	20	21	22	23 ✅ 1.5 hours	24 ✅ 1.5 hours	25	26
	27: Midterm	28	29 ✅ 1.5 hours	30	31 ✅ 1.5 hours	1	2
November	3 ✅ 1.5 hours	4	5 ✅ 1.5 hours	6	7 ✅ 1.5 hours	8	9
	10 ✅ 1.5 hours	11	12 ✅ 1.5 hours	13	14 ✅ 1.5 hours	15	16
	17 ✅ 1.5 hours	18	19 ✅ 1.5 hours	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Gas-filled detectors

- In many particle physics experiments detectors are employed which measure charged particles through their ionization of gases
- Gas-filled detectors allow for the determination of particle trajectories in large volumes, often in a magnetic field
- Compared to semiconductor detectors gaseous detectors are in most cases cheaper, in particular for large volumes, and tend to present less material for the passing particles
- Ionization detectors: best for radiation fluxes containing large number of particles



Kolanoski, Wermes 2015

Fig. 7.1 Principle of an ionisation detector. The sensitive detector medium, in this case gas, resides between two electrodes with a voltage applied across. During the passage of a charged particle through the gas charges are liberated which move in the electric field towards the electrodes. The moving charges induce a current signal at the electrodes (see chapter 5). In principle, the detector is a capacitor which discharges upon ionisation of the medium. Electrically it acts as a current source.

Gas-filled detectors

- Figure below shows as an example the tracks of a three-jet event in the central drift chamber of the TASSO experiment at the PETRA storage ring
- This chamber was put into operation in 1978 and was one of the first large drift chambers comprising a sensitive volume of about 16 m^3 and 2340 readout channels
- Today such detectors for charged particles may have 10^5 or more readout channels

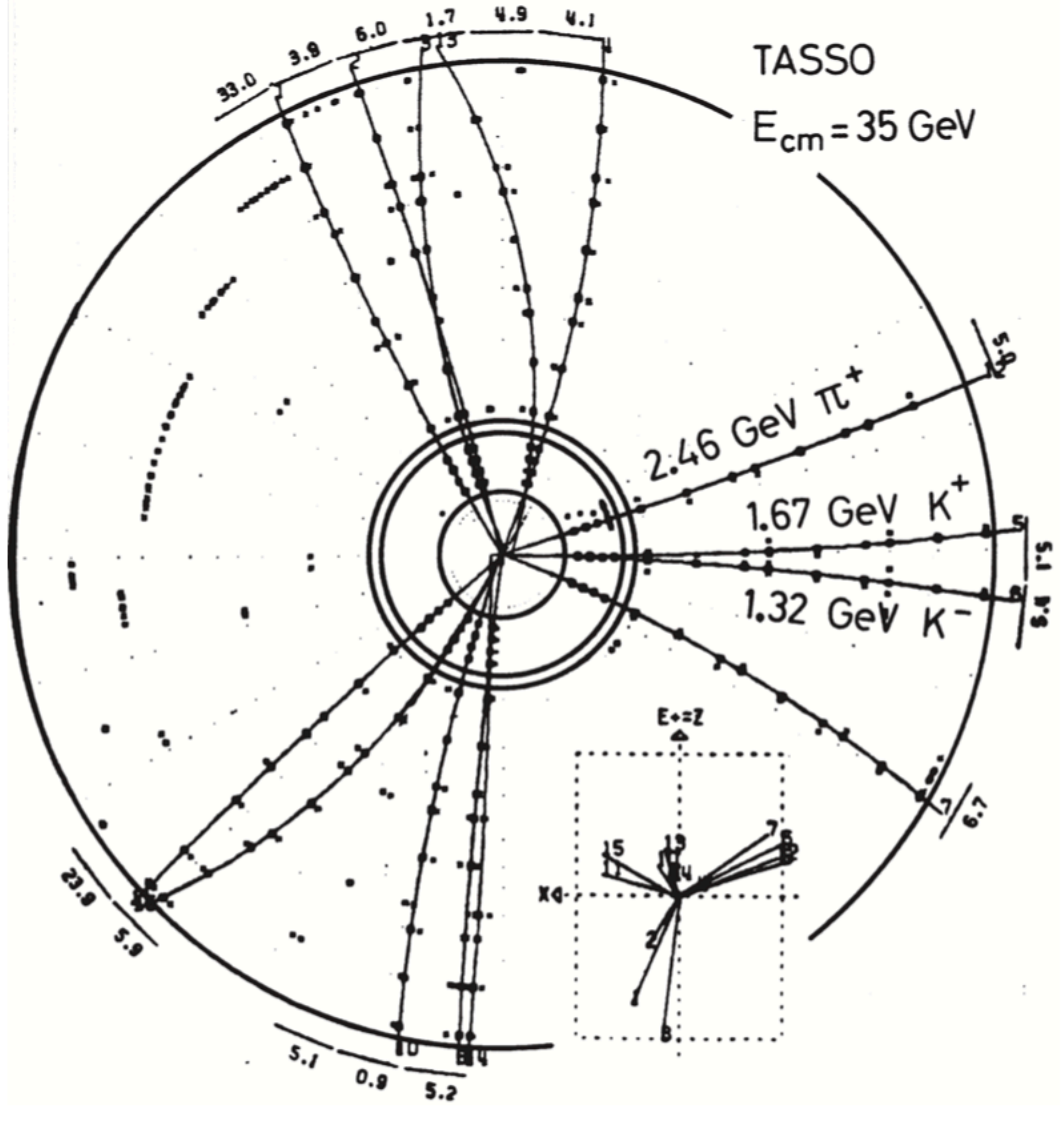
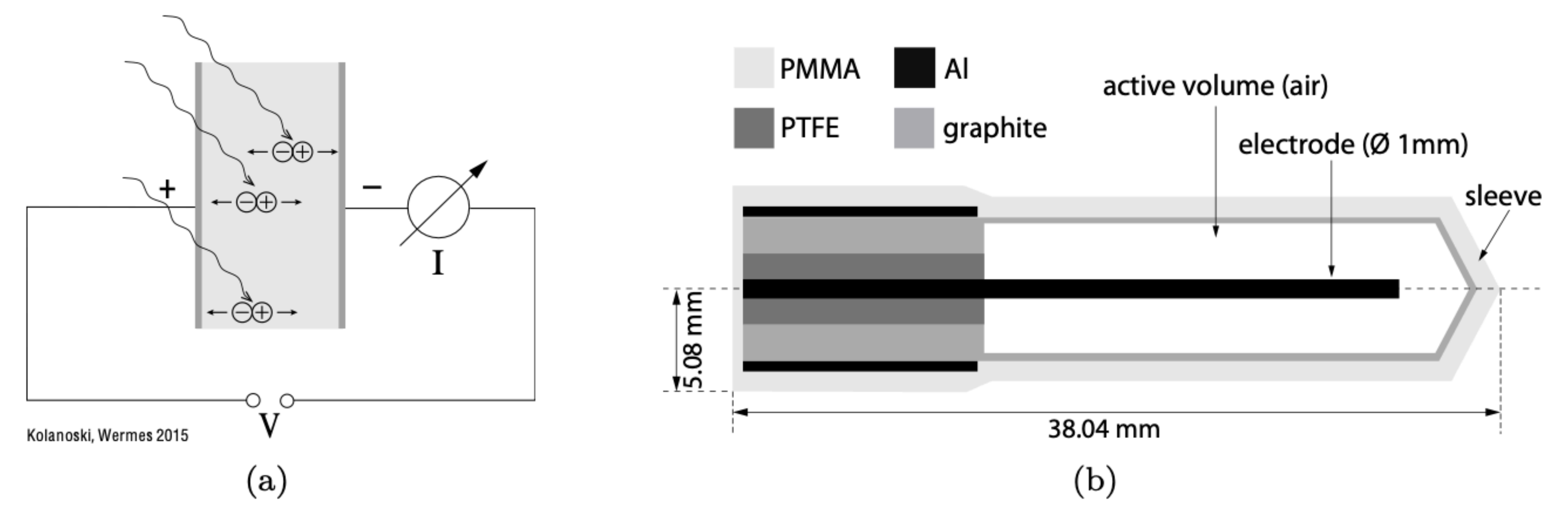


Fig. 7.2 Tracks of charged particles in a three-jet event, interpreted as a quark–antiquark pair with emission of a gluon, in the drift chamber of the TASSO detector at the PETRA storage ring. The picture displays a cross section perpendicular to the colliding electron–positron beams. The insert shows a projection onto a plane containing the beams. Source: DESY.

Detector types

- For different application areas a variety of different detector types exist using gas as the sensitive medium
- Detectors which measure radiation fluxes (radiation monitors such as ionization chambers and proportional counters)
- Those which provide information about the locations where the particle passed the detector (position-sensitive detectors such as multi-wire proportional chambers, drift chambers and gaseous micro-structure detectors)

Ionization chamber is essentially a capacitor, charged up by a voltage V , which discharges due to the ionization in the capacitor volume. The current is a measure of the radiation flux.



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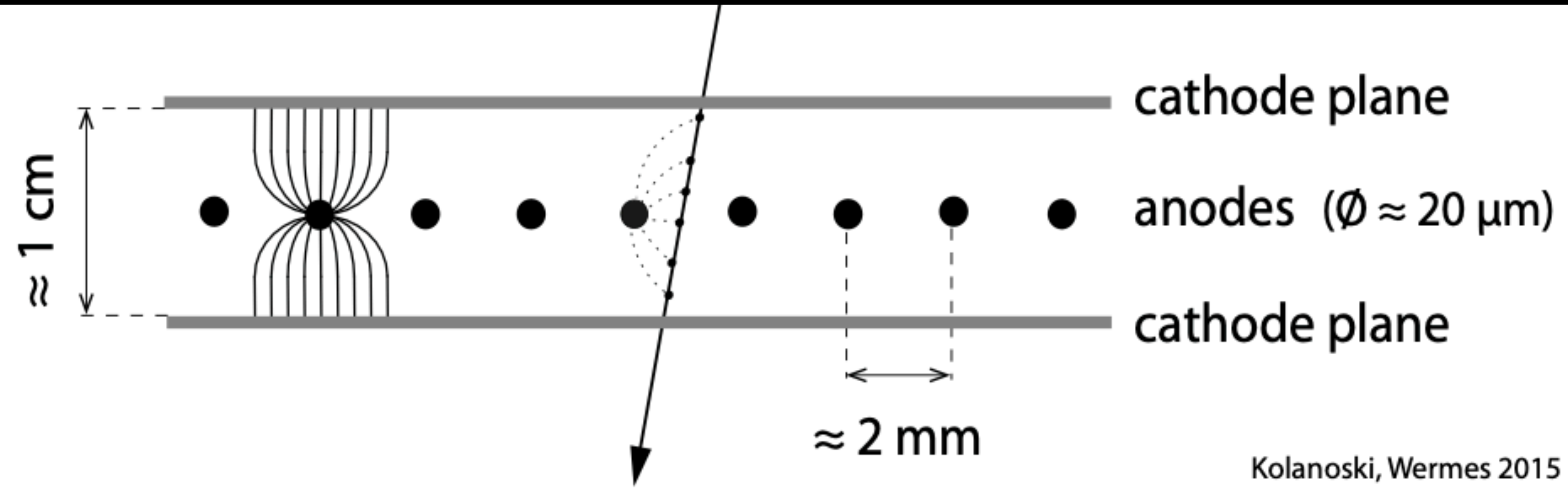
(a)

(b)

Position sensitive detectors

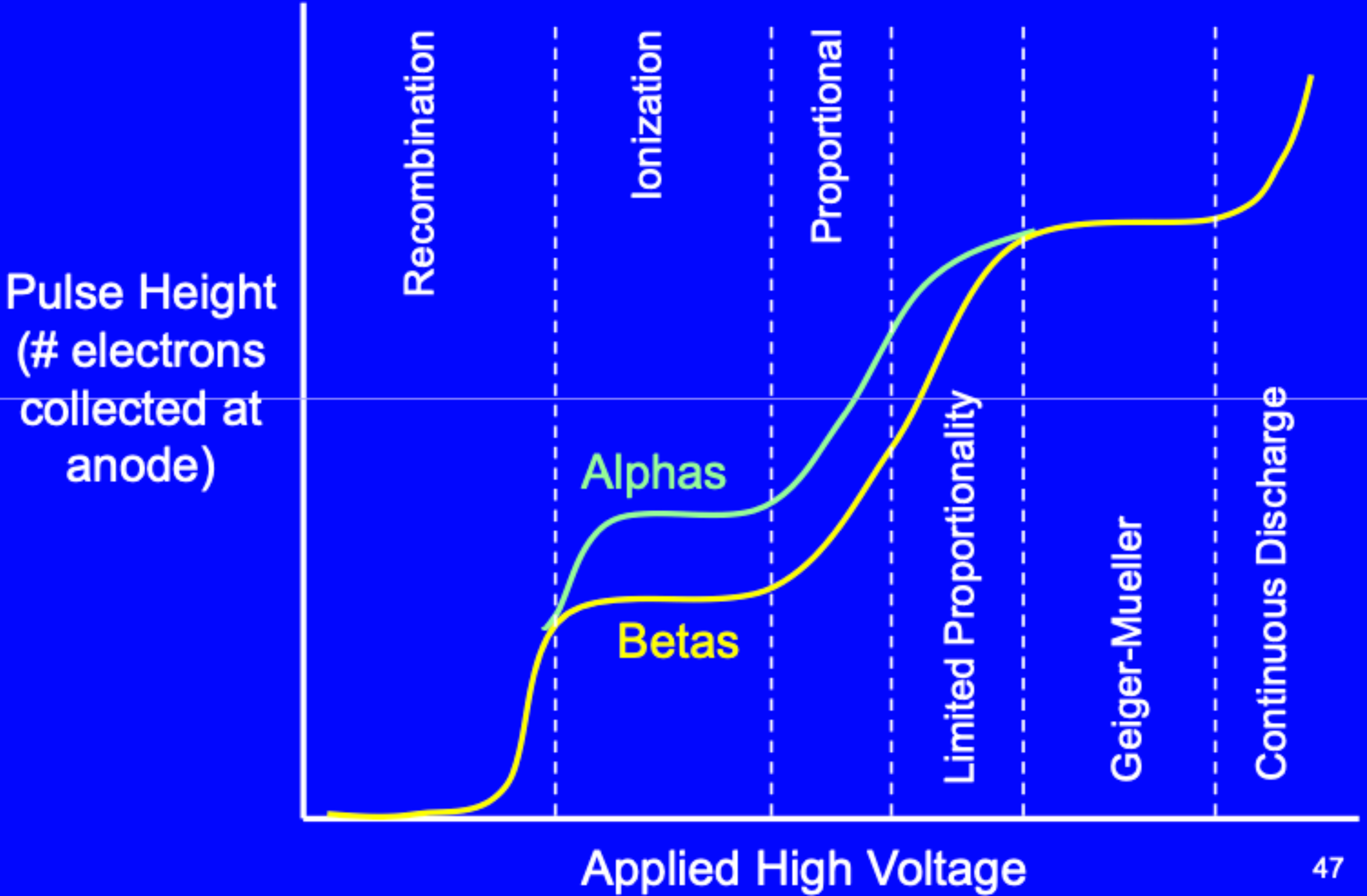
- Basic idea: gas-filled chamber with which the coordinate of a traversing particle can be detected



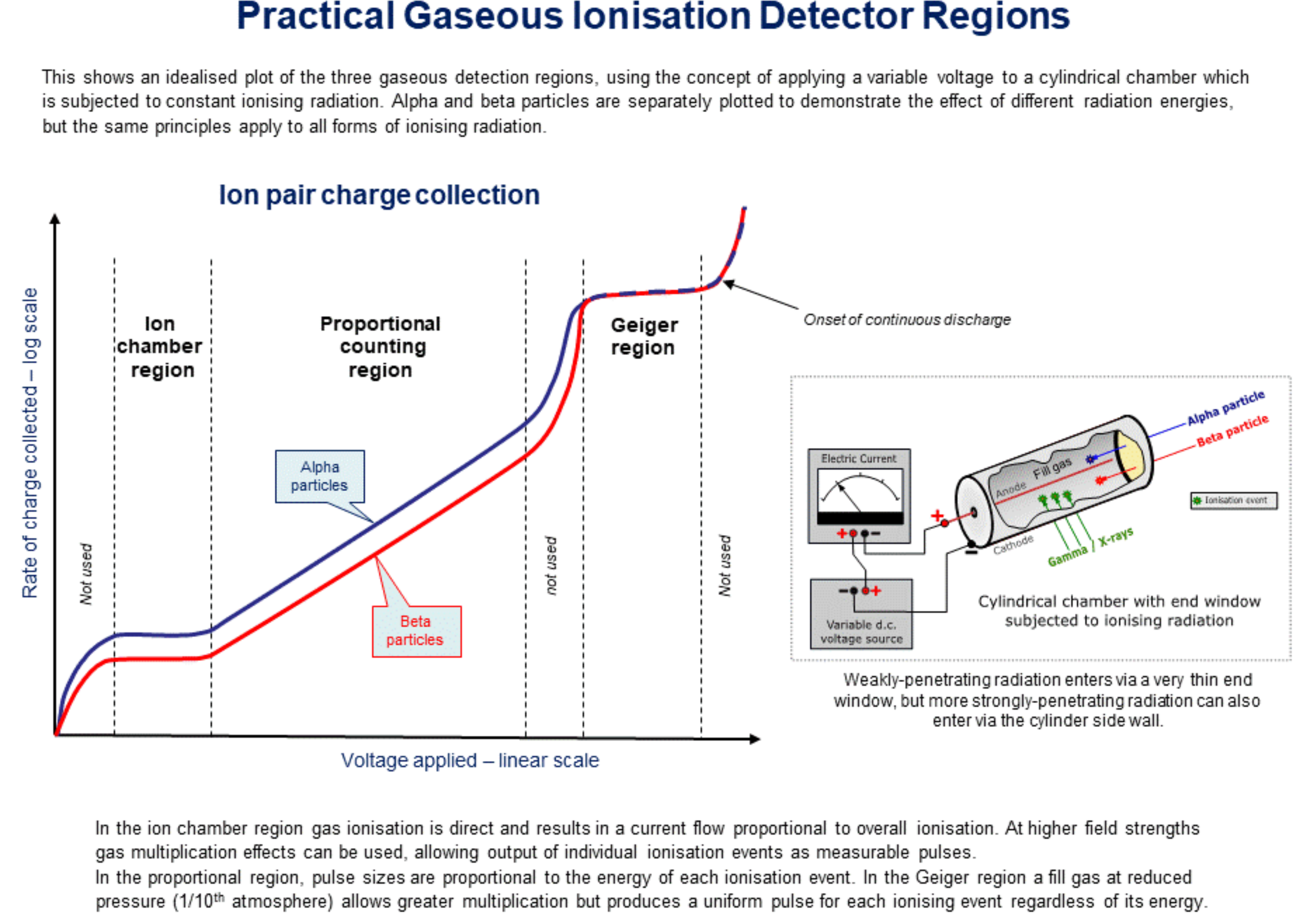
Kolanoski, Wermes 2015

Fig. 7.5 Principle of a position-sensitive multiwire proportional chamber (MWPC). The continuous lines represent the field lines around an anode and the dashed lines the drift paths of electrons generated by ionisation.

The Six Region Curve



Basic principle



Practical Gaseous Ionisation Detector Regions

This shows an idealised plot of the three gaseous detection regions, using the concept of applying a variable voltage to a cylindrical chamber which is subjected to constant ionising radiation. Alpha and beta particles are separately plotted to demonstrate the effect of different radiation energies, but the same principles apply to all forms of ionising radiation.

Ion pair charge collection

Cylindrical chamber with end window subjected to ionising radiation

Weakly-penetrating radiation enters via a very thin end window, but more strongly-penetrating radiation can also enter via the cylinder side wall.

In the ion chamber region gas ionisation is direct and results in a current flow proportional to overall ionisation. At higher field strengths gas multiplication effects can be used, allowing output of individual ionisation events as measurable pulses.
In the proportional region, pulse sizes are proportional to the energy of each ionisation event. In the Geiger region a fill gas at reduced pressure (1/10th atmosphere) allows greater multiplication but produces a uniform pulse for each ionising event regardless of its energy.

Region 1: Recombination Region

- Recombination region:
  - At the lowest voltages, the strength of the electric field is sufficiently low that many of the primary ion pairs created in the gas by the incident charged particle simply recombine
  - If no electrons reach the anode, there is no pulse

Region 2: Ionization Region

- Ionization region:
  - In the ionization region, the electric field is just strong enough to prevent recombination of the ion pairs produced in the gas
  - At least one electron reaches the anode for each primary ion pair created by the incident radiation

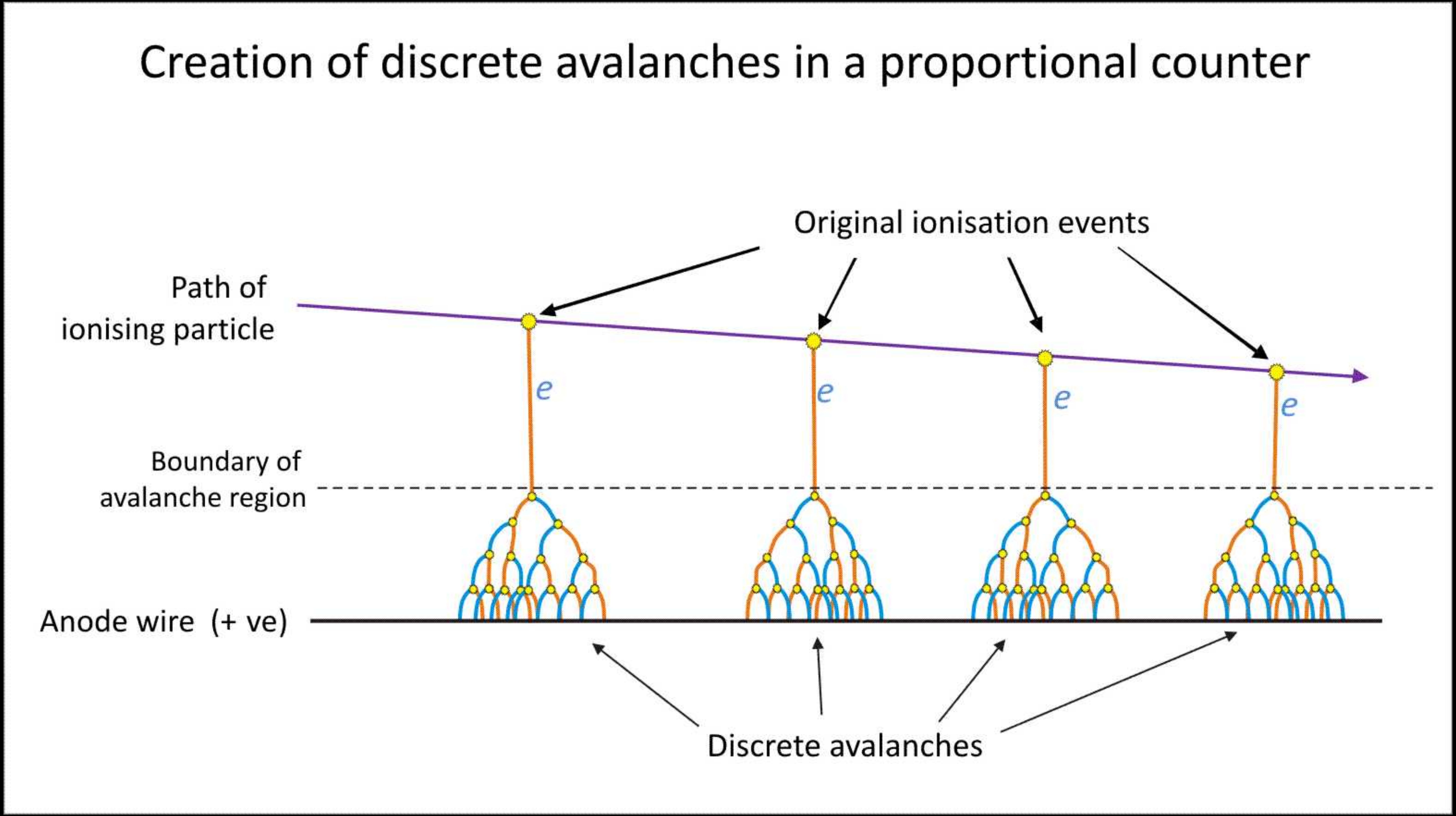
Region 3: Proportional Region

- Proportional region:
  - The applied high voltage is greater and the electric field is substantially stronger than in the ionization region
  - When the electric field is strong, electrons gain enough kinetic energy to create secondary ion pairs
  - The electrons produced in these secondary ion pairs, along with the primary electrons, continue to gain energy as they move towards the anode, and as they do, they produce more and more ionizations

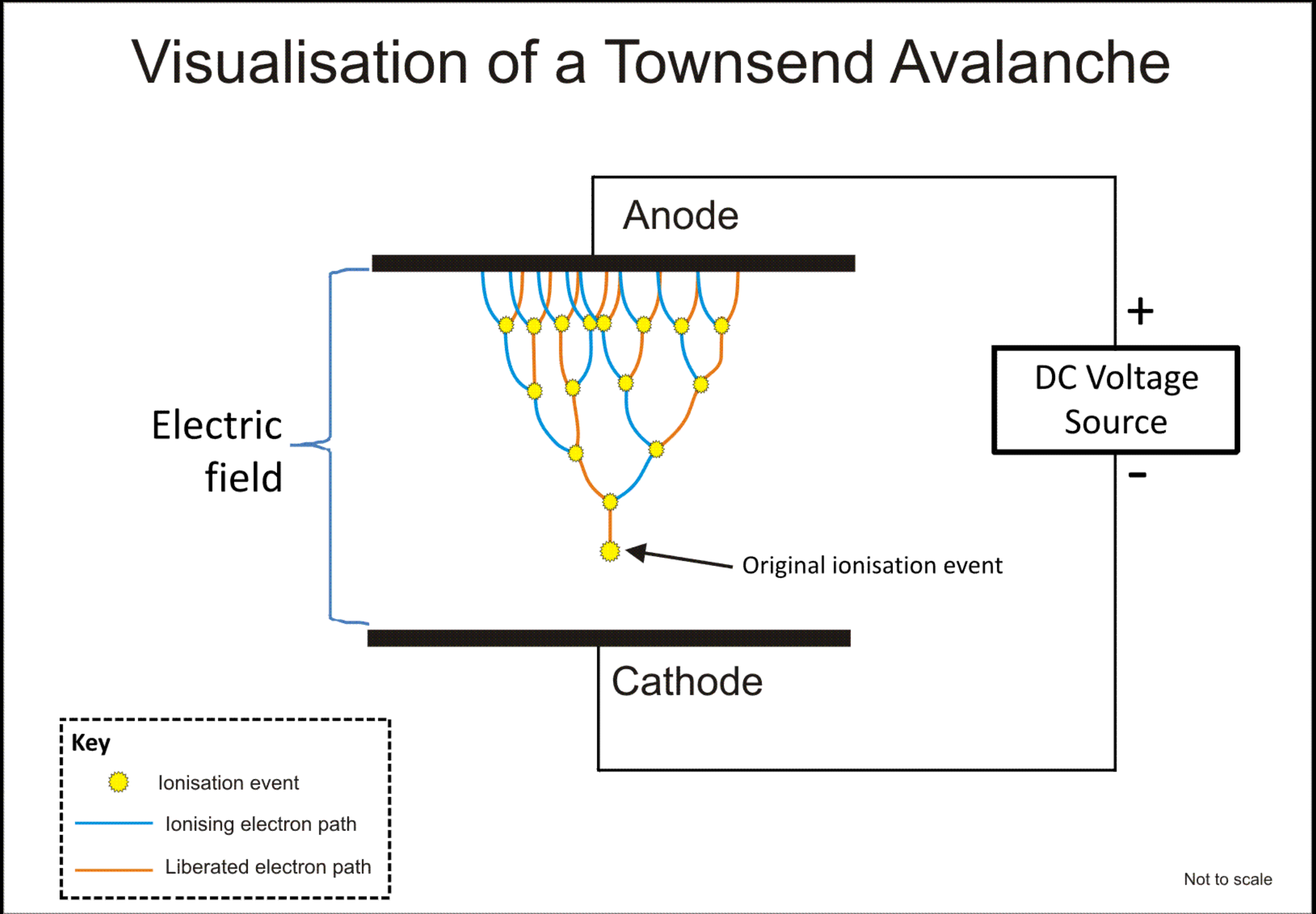
Region 3: Proportional Region

- Proportional region:
  - The result is that each electron from the primary ion pairs produces a cascade, or avalanche of ion pairs (Townsend avalanche)
  - For every primary ion pair created in the chamber by the ionizing radiation, 10^2 to 10^4 electrons reach the anode
  - The increase in the number of electrons is referred to as the multiplication factor
  - As the high voltage increases, the distance from the anode at which the field strength exceeds $10^6\ V/m$ increases
  - As the avalanches are initiated further away from the anode, the multiplication factor (and pulse size) increases

Basic principle



Basic principle



Region 4: Region of Limited Proportionality

- Region of Limited Proportionality
  - The high voltage and the multiplication factor are larger than in the proportional region
  - What is now different is that pulse size is no longer linearly related to the number of primary ion pairs produced by the incident radiation. In other words, doubling the number of primary ion pairs, doesn’t double the pulse size
  - This increases the uncertainty of using pulse size to distinguish different types of radiation

Region 5: Geiger-Mueller Region

- Geiger-Mueller Region
  - At the high voltages associated with the Geiger-Mueller Region, the avalanche spreads along the complete length of the anode
    - avalanches not only involve ionization, they also involve the excitation of gas molecules. When excited molecules in an avalanche de-excite, they can emit UV photons
  - In this region, the size of the pulse is totally independent of the number of primary ion pairs produced by the incident radiation
  - In other words, alpha particles, beta particles and photons produce pulses of exactly the same size
  - There is a complete loss of proportionality between the radiation energy deposited in the detector gas and the pulse size

Region 6: Continuous discharge

- Continuous discharge
  - In this region, arcing will occur that can result in a complete breakdown of the gas
  - Any extended operation in this region will destroy the tube

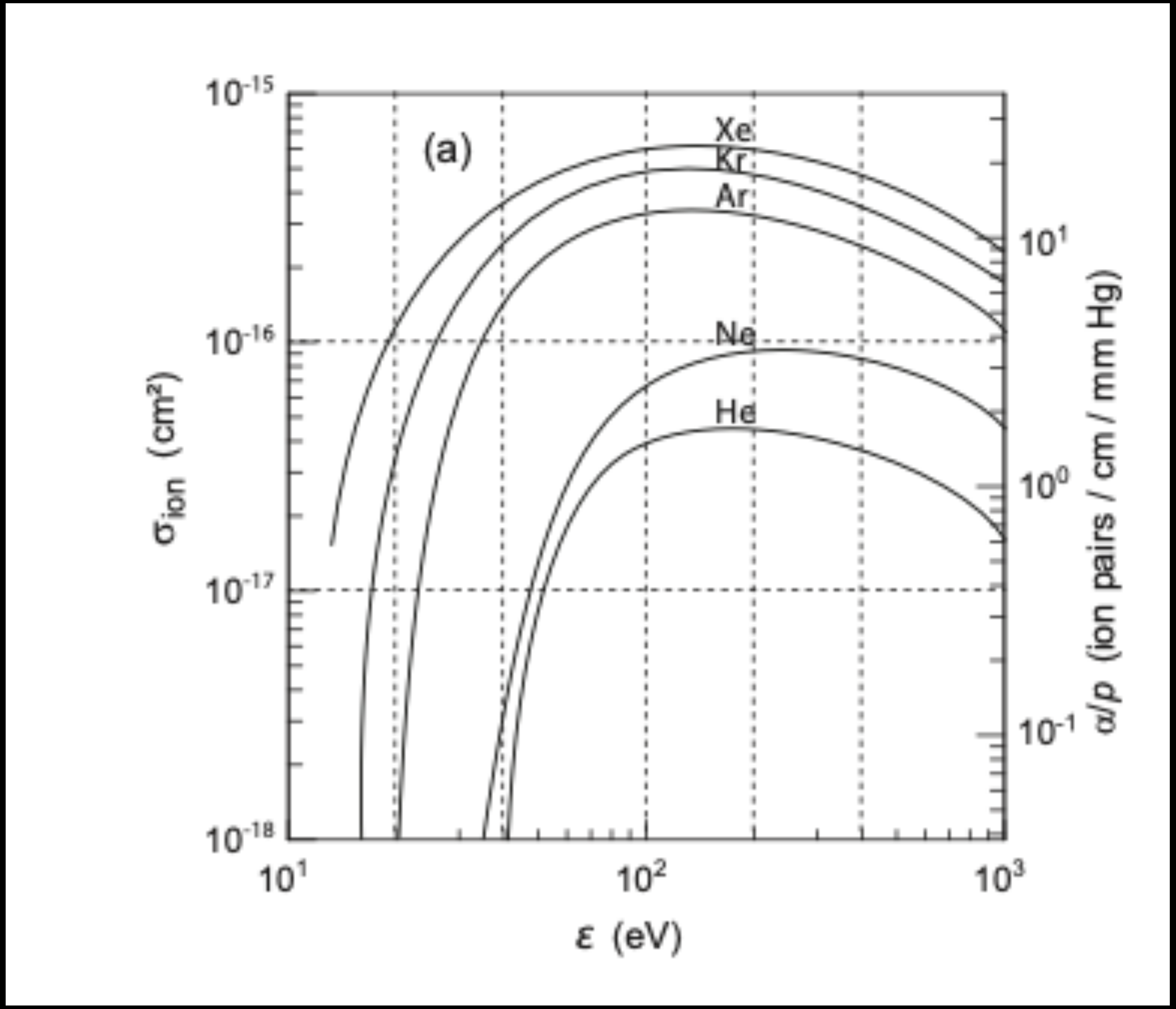
Gas amplification

- If the electric field is strong enough (near the anode of a wire chamber), the drifting electrons can be accelerated such that they can initiate secondary ionizations
  - An avalanche developed and the ionization change is amplified with typical amplification factors of $10^4 - 10^6$
  - The number α of ions generated per path length, the so-called first Townsend coefficient is given by:
    - $\alpha = \sigma_{ion} n = \dfrac{1}{\lambda_{ion}}$ where σ_{ion} and λ_{ion} are the cross section for ionization and mean free path between ionizations, respectively
    - n = molecule density

Gas amplification

- The increase dN of the number of electron-ion pairs over a path length ds is:
  - $dN = \alpha(E)\ N\ ds$

The ionization cross section and the first Townsend coefficient for electrons in various noble gases as a function of the electron energy



Gas amplification

- The increase dN of the number of electron-ion pairs over a path length ds is:
  - $dN = \alpha(E)\ N\ ds$
- It follows that:
  - $N(s_a) = N_0 \exp\left(\int_{s_0}^{sa} \alpha(E(s))\ ds\right)$
  - N_0: number of unamplified electrons at $s = s_0$, where the amplification starts
  - $N(s_a)$: number of electrons which reach the anode at $s = s_a$
  - The ratio of both numbers defines the gas amplification G :
    - $G := \dfrac{N(s_a)}{N_0} = \exp\left(\int_{s_0}^{s_a} \alpha(E(s))\ ds\right)$
    - If α does not depend on s, this yields:
      - $G = \exp(\alpha(s_a - s_0))$

Gas amplification

- We can estimate the number of collisions necessary to obtain such an amplification by assuming that the number of electrons duplicates at each collision:
  - $G = 2^n \implies n = 13 - 20$
  - Empirically $n = 8$
  - In this estimate half of all charges in the avalanche are created on the last mean free path length
    - most of the electrons have a vanishingly small drift path to the anode while the ions have to traverse a long way to the cathode

Gas amplification — in a cylindrical geometry

- For a cylindrical geometry:
- $$\ln G = \frac{kV}{\ln \frac{b}{a}} \ln \left(\frac{E(a)}{E_{min}} \right)$$

Operation modes of gaseous detectors

- Recombination region $G < 1$:
  - In the region of low field strengths the primary electrons and ions recombine with increased probability if they are not sufficiently quickly separated
- Ionization chamber region $G \approx 1$:
  - The saturation of the output signal without amplification defines the regime in which ionization chambers are operated. This op- eration mode is suited for measurements of particle fluxes, as for example done with dosimeters
  - Not suited for the detection of single particles since without amplification the signal charge of single particles is too small for detection

Operation modes of gaseous detectors

- Proportional region, $G \approx 10^3 - 10^5$:
  - If in a strong field electrons gain sufficient energy between two collisions to produce secondary electrons, a charge avalanche develops
  - With increasing operation voltage the amplified charge is proportional to the primary charge
- Region of limited proportionality, $G \approx 10^5 - 10^8$:
  - With increasing voltage the proportionality of the output signal to the primary ionization will be limited by space charge effects. At sufficiently high amplification an ion cloud builds up at the anode which only slowly drifts away because of the relatively small mobility of the ions. This charge cloud diminishes the field locally around the anode wire

Operation modes of gaseous detectors

- Saturation and Geiger region, $G \geq 10^8$:
  - With further increasing gas amplification the output signal finally becomes independent of the primary ionization
- Discharge region, above $G \approx 10^8 - 10^9$:
  - At very high voltages self-sustaining discharges occur, either spontaneously or triggered by ionizing particles

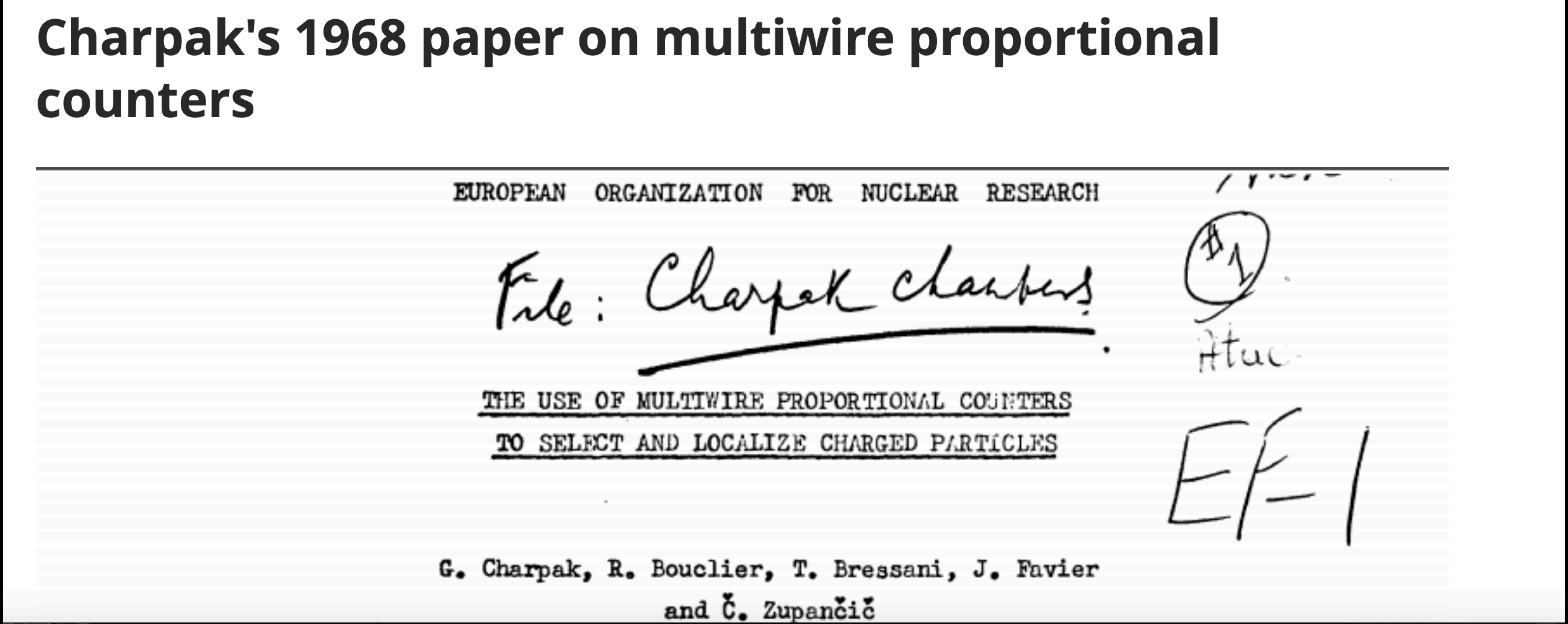
Choice of gaseous medium

- Main criteria dictated by:
  - high ionization density
  - little charge loss
  - low voltage at the required amplification
  - stable operation, safety against spark discharge
  - proportionality between ionisation and output signal
  - low diffusion (in particular for detectors with position resolution)
  - suitable drift velocity (again for detectors with position resolution)
  - rate tolerance and low or minor dead time (low space charge accumulation)
  - radiation resistance
  - safety: non-inflammable, non-toxic, environmentally acceptable
  - costs

Multi-wire proportional chambers

- A multiwire proportional chamber (MWPC) functions like proportional counter with tubes that are arranged in a plane side by side
- Such an arrangement provides spatial resolution perpendicular to the wires for particles passing the wire plane
- With several MWPC planes stacked behind each other the trajectories of charged particles can be electronically registered (in contrast, for example, to bubble chambers which are read out photographically)
- The MWPC was developed by George Charpak at CERN in the late 1960s
- This detector type and variants of it, like the drift chamber, have been crucial for progress in particle physics
- George Charpak received the Nobel Prize in 1992 ‘for his invention and development of particle detectors, in particular the multiwire proportional chamber’

Multi-wire proportional chambers



Charpak's 1968 paper on multiwire proportional counters

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File: Charpak chambers

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THE USE OF MULTIWIRE PROPORTIONAL COUNTERS
TO SELECT AND LOCALIZE CHARGED PARTICLES

G. Charpak, R. Bouclier, T. Bressani, J. Favier
and Č. Zupančič

https://home.cern/resources/publication/accelerators/charpaks-1968-paper-multiwire-proportional-counters

Multi-wire proportional chambers

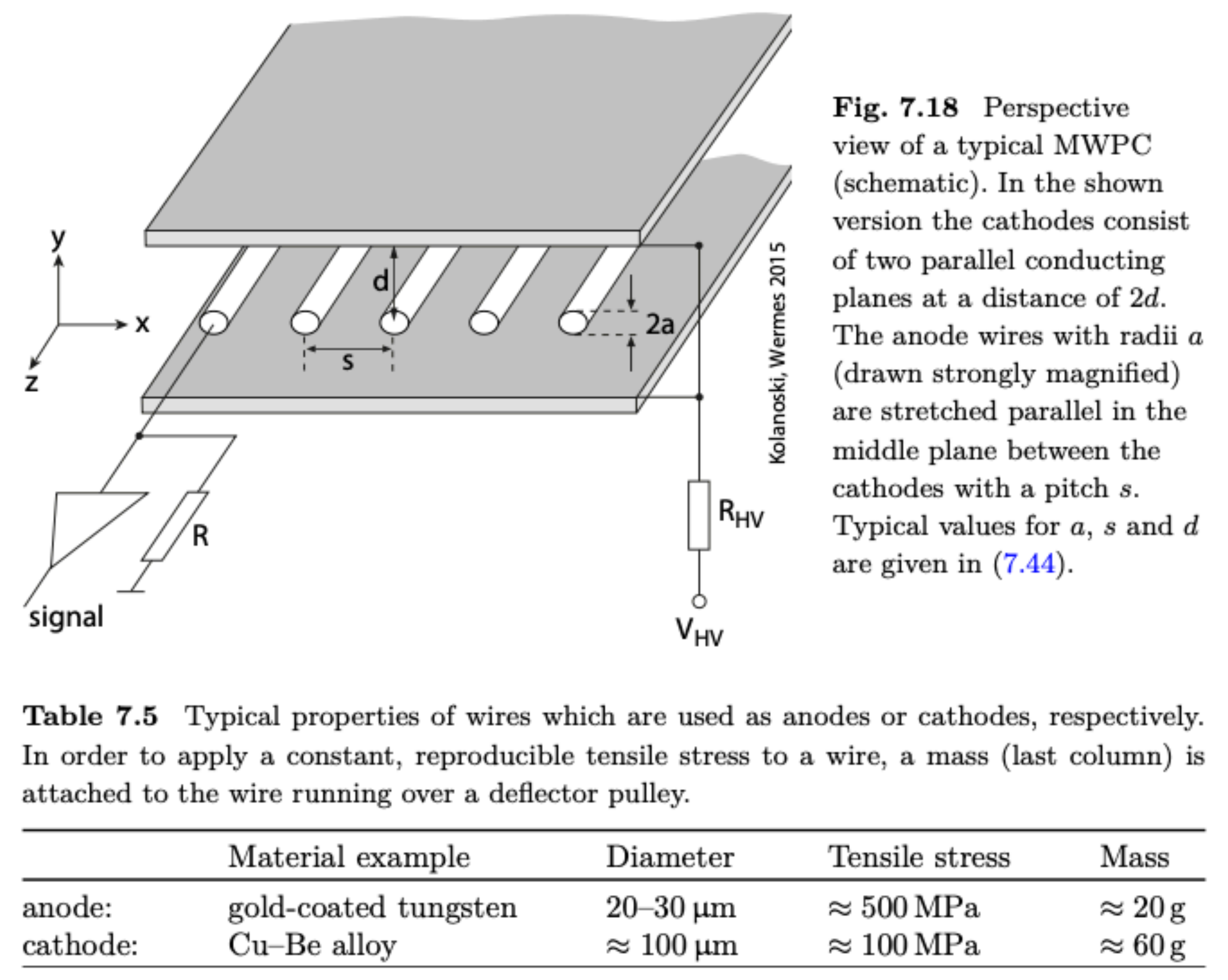

Fig. 7.18 Perspective view of a typical MWPC (schematic). In the shown version the cathodes consist of two parallel conducting planes at a distance of $2d$. The anode wires with radii a (drawn strongly magnified) are stretched parallel in the middle plane between the cathodes with a pitch s. Typical values for a, s and d are given in (7.44).

Table 7.5 Typical properties of wires which are used as anodes or cathodes, respectively. In order to apply a constant, reproducible tensile stress to a wire, a mass (last column) is attached to the wire running over a deflector pulley.

	Material example	Diameter	Tensile stress	Mass
anode:	gold-coated tungsten	20–30 µm	≈ 500 MPa	≈ 20 g
cathode:	Cu–Be alloy	≈ 100 µm	≈ 100 MPa	≈ 60 g

Literature survey

- Do some literature survey and identify current or older particle physics experiments that used gas filled detectors in prominent ways