内部飛跡検出器

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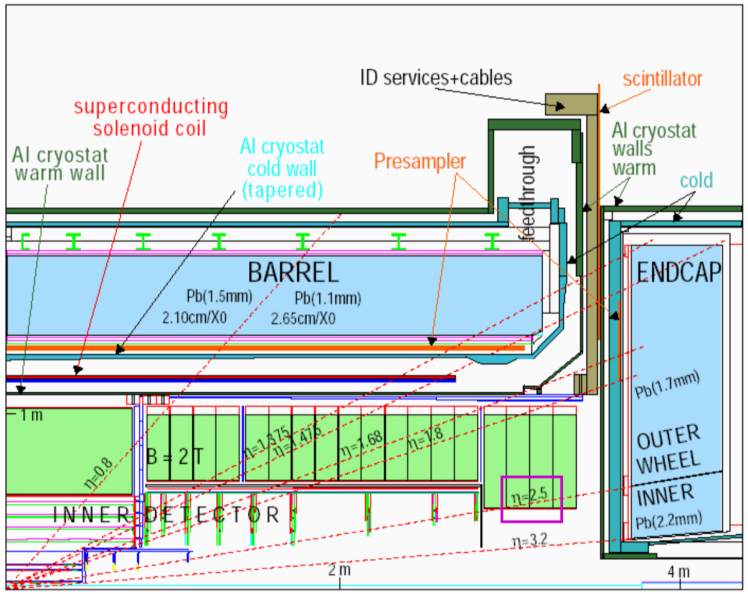
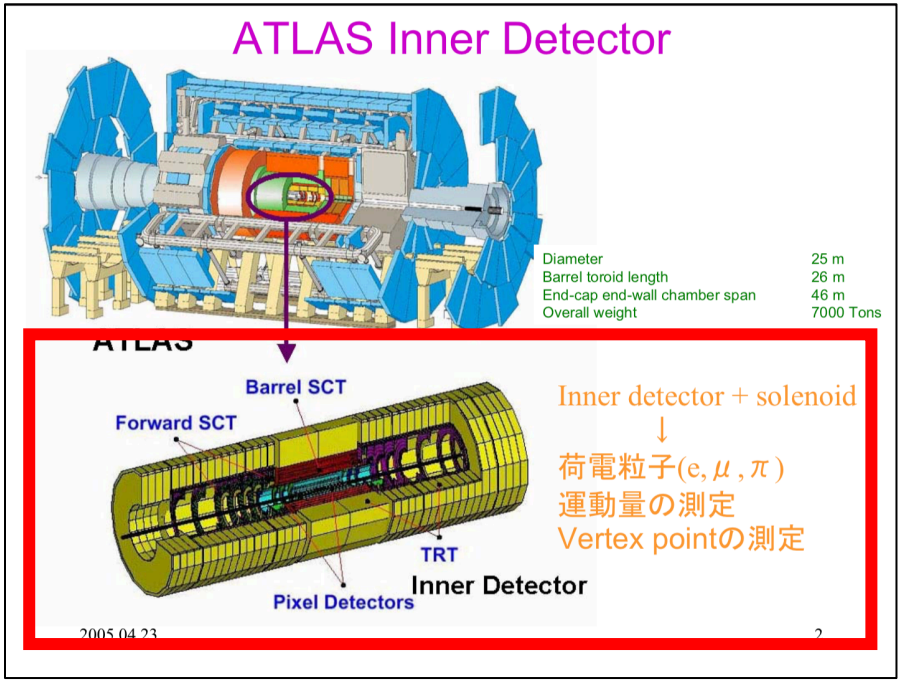
ATLAS内部飛跡検出器

◎長さ：44m

◎直径：25m

◎重さ：7000t



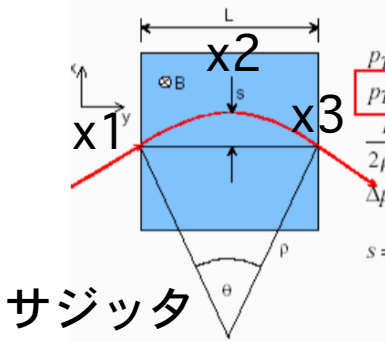


$$\eta = -\ln[\tan\frac{\theta}{2}]$$

カロリーメータの様子

運動量の測定分解能

Momentum measurement



$$p_T = qB\rho$$

$$\boxed{p_T\,(\mathrm{GeV}/c) = 0.3B\rho \quad (\mathrm{T\cdot m})}$$

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L\cdot B}{p_T}$$

$$\Delta p_T = p_T \sin\theta \approx 0.3L\cdot B$$

$$s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

the sagitta s is determined by 3 measurements with error $\sigma(x)$: $s = x_2 - \frac{x_1 + x_3}{2}$

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8\,p_T}{0.3\cdot BL^2}$$

for N equidistant measurements, one obtains
(R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad (\text{for } N \geq \approx 10)$$

ex: p_T=1 GeV/c, L=1m, B=1T, σ(x)=200μm, N=10

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\% \qquad (s \approx 3.75\ \mathrm{cm})$$

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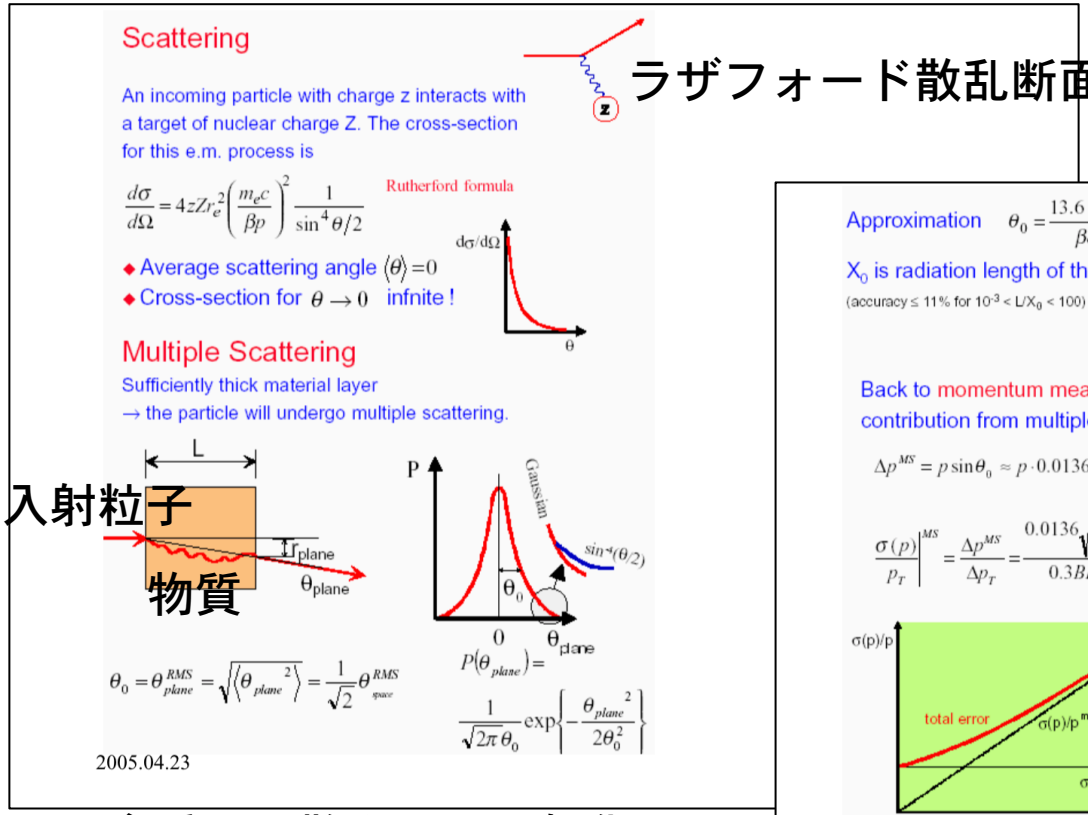
$\sigma(1/pt) \propto \sigma x$

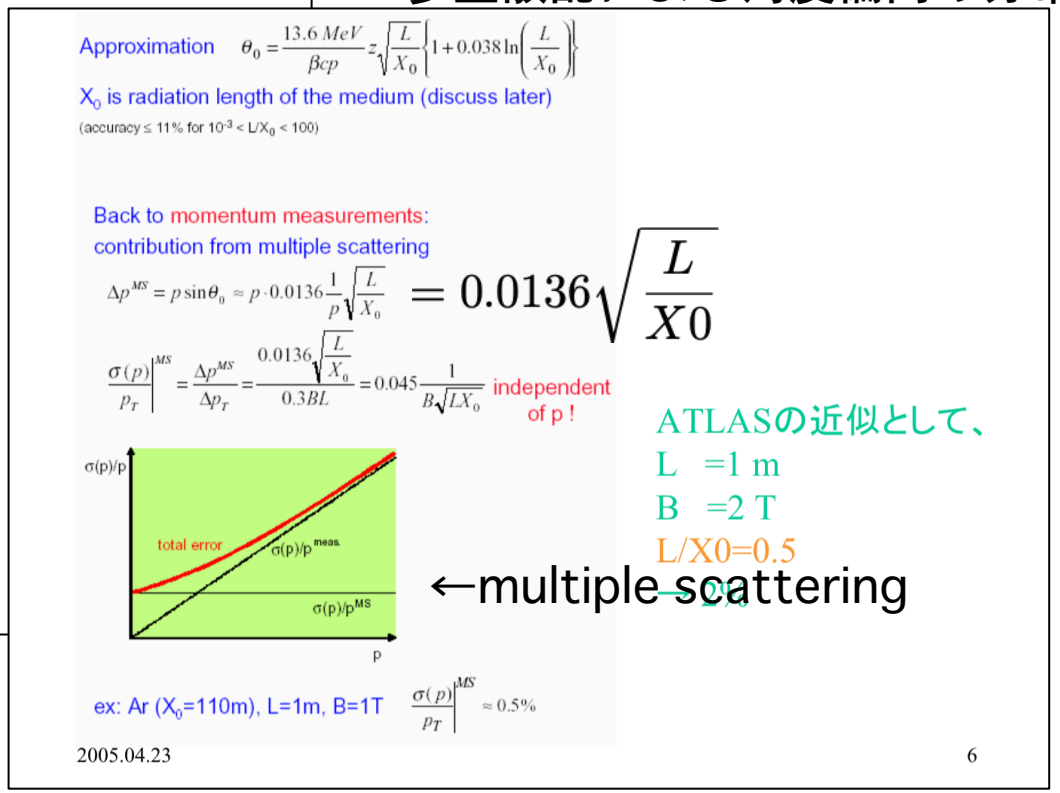
ATLASの近似として、
Pt =500 GeV/c
L =1 m
B =2 T
σx=60 μ m
N =50
→ 20 %

運動量分解能(多重散乱の影響)



ラザフォード散乱断面積

多重散乱による角度偏向の分布



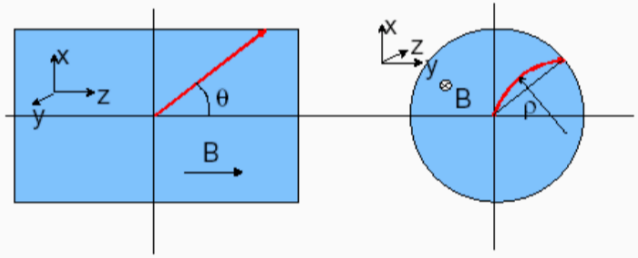
ATLASの近似として、
L =1 m
B =2 T
L/X0=0.5
→ 0.4

←multiple scattering

多重回の散乱へと一般化
→角度分解能を低下させる

運動量分解能(角度分解能)

Momentum measurement in experiments with solenoid magnet:



$p_T = p\sin\theta$

polar angle has to be determined from a straight line fit x=x(z).

N equidistant points with error $\sigma(z)$

$$\sigma(\theta)\Big|^{meas.} = \frac{\sigma(z)}{L}\sqrt{12(N-1)/(N(N+1))}$$

+ multiple scattering contribution.... } normally small

In practical cases: $\frac{\sigma(p)}{p} \approx \frac{\sigma(p_T)}{p_T}$

In summary: $\boxed{\frac{\sigma(p)}{p}\Big|^{meas.} \propto \frac{\sigma(x)\cdot p}{BL^2}\frac{1}{\sqrt{N}}}$

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θ resolution

total momentum error

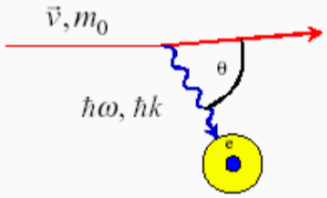
$$\left(\frac{\sigma(p)}{p}\right)^2 = \left(\frac{\sigma(p_T)}{p_T}\right)^2 + \cot^2(\theta)\sigma_\theta \simeq \left(\frac{\sigma(p_T)}{p_T}\right)^2$$

荷電粒子の検出

Detection of charged particles

How do they loose energy in matter ?

- Discrete collisions with the atomic electrons of the absorber material.



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar\, d\omega$$

N : electron density

Collisions with nuclei not important ($m_e << m_N$).

- If $\hbar\omega, \hbar k$ are big enough ⇨ ionization.

Instead of ionizing an atom, under certain conditions the photon can also escape from the medium.

⇨ Emission of **Cherenkov** and **Transition** radiation. (See later).

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入射粒子が物質と相互作用
→エネルギー損失
→物質をイオン化

→チェレンコフ光
→遷移放射(後述)

エネルギー損失

荷電粒子が物質の電子との電磁相互作用
→エネルギー損失

Average differential energy loss $\left\langle \frac{dE}{dx} \right\rangle$

Ionisation only → Bethe - Bloch formula

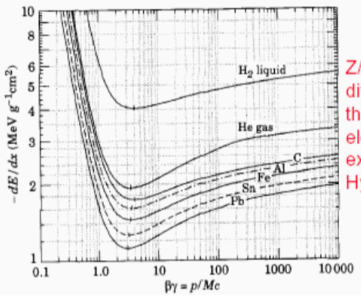
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{max} - \beta^2 - \frac{\delta}{2}\right]$$

- dE/dx in [MeV g^{-1} cm^2]
- dE/dx depends only on β, independent of m
- Formula takes into account energy transfers

$I \le dE \le T^{max}$ I : mean excitation potential

$I \approx I_0 Z$ with $I_0 = 10$ eV (rough approximation, I fitted for each element)

- Bethe-Bloch formula only valid for "heavy" particles ($m \gtrsim m_\mu$).
- Electrons and positrons need special treatment ($m_{proj}=m_{target}$), in addition Bremsstrahlung!



Z/A does not differ much for the various elements, except for Hydrogen!

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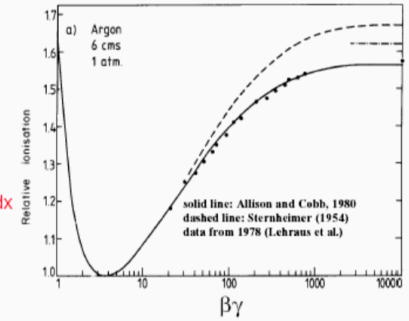
T^{max} ：一回の衝突で
自由電子に与えられる
最大の運動エネルギー

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{max} - \beta^2 - \frac{\delta}{2}\right]$$

- dE/dx first falls ∝ $1/\beta^2$ (more precise $\beta^{-5/3}$), kinematic factor
- then minimum at $\beta\gamma \approx 4$ (minimum ionizing particle, MIP) (dE/dx ≈ 1 - 2 MeV g^{-1} cm^2)
- then again rising due to $\ln\gamma^2$ term, relativistic rise, attributed to relativistic expansion of transverse E-field → contributions from more distant collisions.
- relativistic rise cancelled at high γ by "density effect", polarization of medium screens more distant atoms. Parameterized by δ (material dependent) → Fermi plateau
- many other small corrections

粒子が単位長さ当たりに
落とす平均エネルギー

Measured and calculated dE/dx



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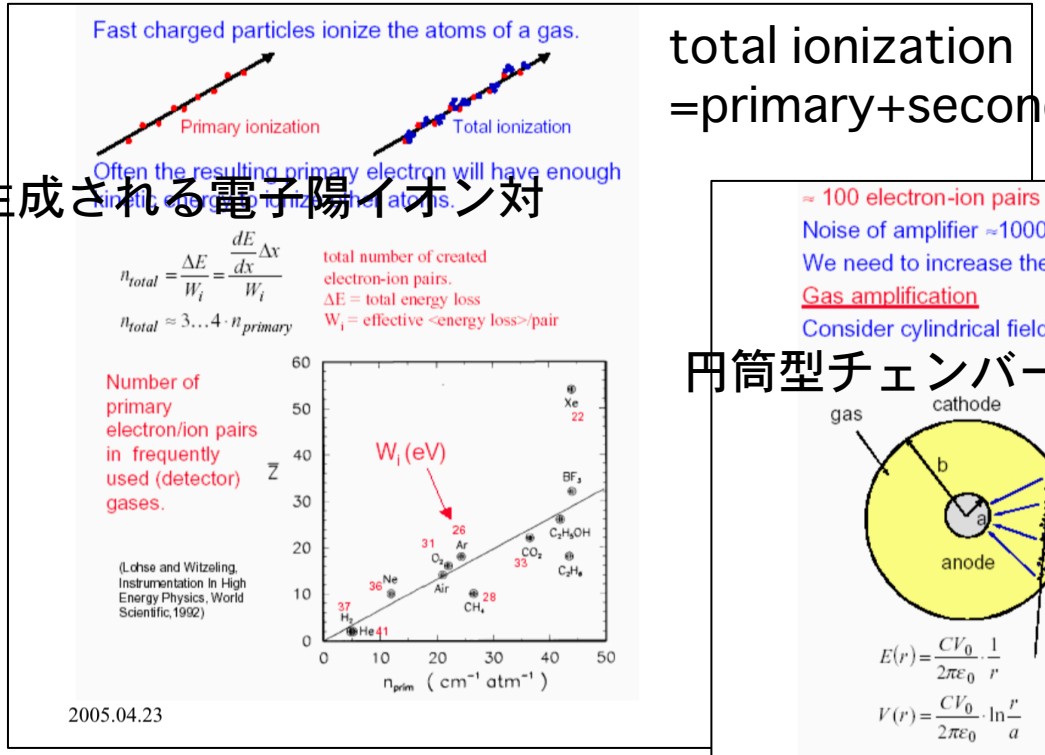
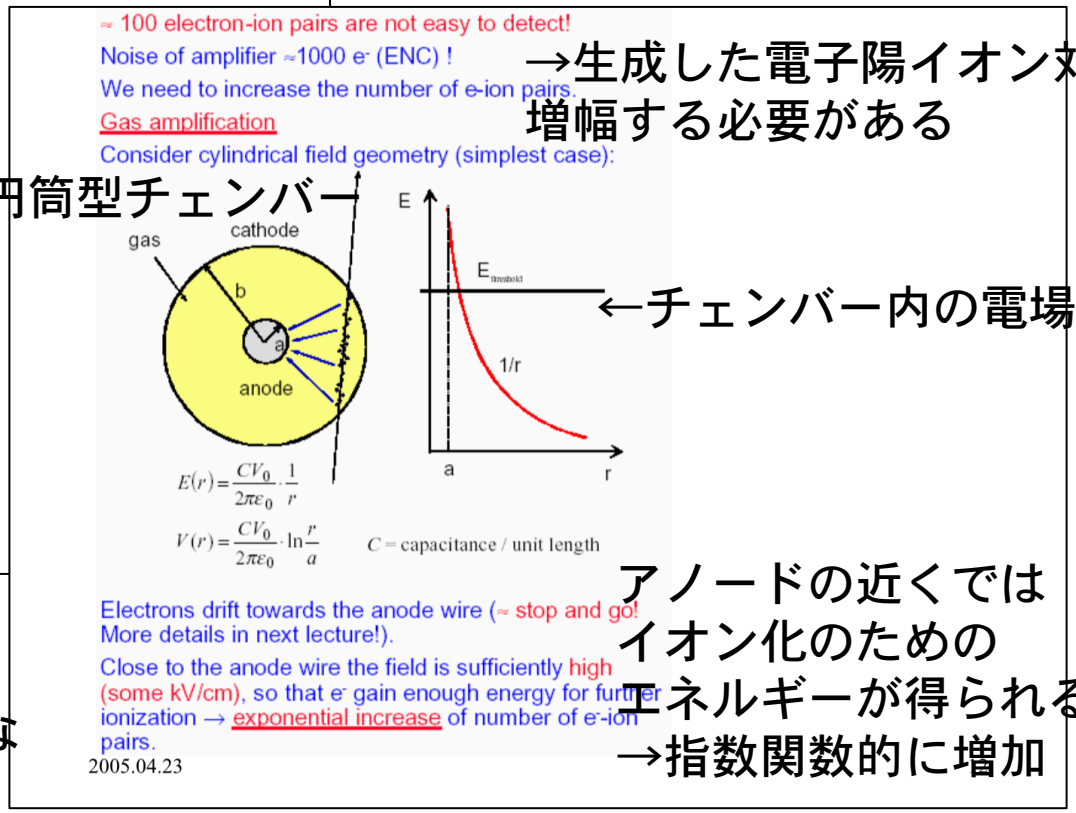
イオン化



total ionization
=primary+secondary(ionization)

生成される電子陽イオン対

ΔE:入射荷電粒子が失った平均エネルギー
W:電子陽イオン対生成に必要な平均エネルギー



→生成した電子陽イオン対を増幅する必要がある

円筒型チェンバー

←チェンバー内の電場

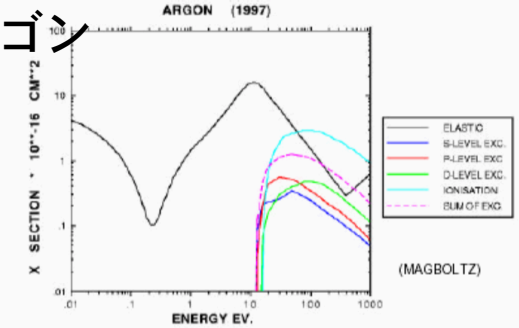
アノードの近くではイオン化のためのエネルギーが得られる
→指数関数的に増加

ガス選択

Choice of gas:

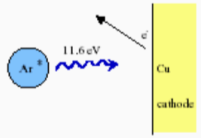
Dense noble gases. Energy dissipation mainly by ionization! High specific ionization.

アルゴン



De-excitation of noble gases only possible via emission of photons, e.g. 11.6 eV for Argon.

This is above ionization threshold of metals, e.g. Copper 7.7 eV.



→ new avalanches → permanent discharges !

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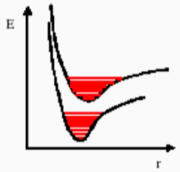
希ガス：衝突によるエネルギーを効率良く電離作用に変換することができる

Solution: Add poly-atomic gases as quenchers.

Absorption of photons in a large energy range (many vibrational and rotational energy levels).

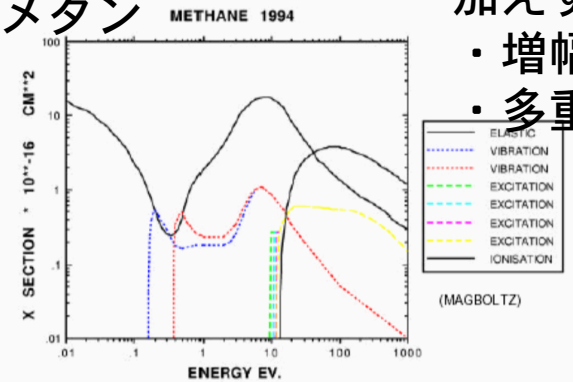


Energy dissipation by collisions or dissociation into smaller molecules.

→多原子ガスを加える
光子吸収断面積が大きい

Methane: absorption band 7.9 - 14.5 eV

メタン



加えすぎると…
- 増幅が下がる
- 多重散乱が起こりやすい

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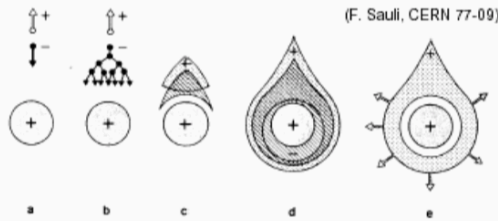
十分なgainを得る前に放電が生じてしまう

電子雪崩

Signal formation

(F. Sauli, CERN 77-09)



電子雪崩の時間発展

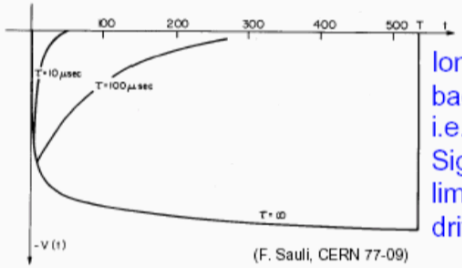
Avalanche formation within a few wire radii and within t < 1 ns!

Signal induction both on anode and cathode due to moving charges (both electrons and ions).

$$dv = \frac{Q}{lCV_0}\frac{dV}{dr}dr$$

誘起された信号

Electrons collected by anode wire, i.e. *dr* is small (few µm). Electrons contribute only very little to detected signal (few %).



Ions have to drift back to cathode, i.e. *dr* is big. Signal duration limited by total ion drift time !

(F. Sauli, CERN 77-09)

電子のドリフト時間を測定している間は他の粒子を測定することはできない

Need electronic signal differentiation to limit dead time.

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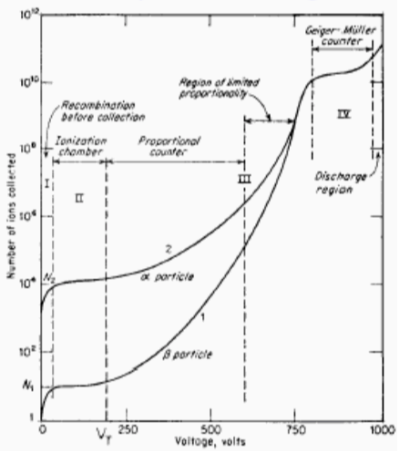
印加電圧とガス増幅率の関係

- ionization mode: full charge collection, but no charge multiplication.
- Proportional mode: above threshold voltage multiplication starts. Detected signal proportional to original ionization → energy measurement (dE/dx). Secondary avalanches have to be quenched. Gain 10^4 - 10^5.
- Limited Proportional → Saturated → Streamer mode: Strong photo-emission. Secondary avalanches, merging with original avalanche. Requires strong quenchers or pulsed HV. High gain (10^{10}), large signals → simple electronics.
- Geiger mode: Massive photo emission. Full length of anode wire affected. Stop discharge by cutting down HV. Strong quenchers needed as well.



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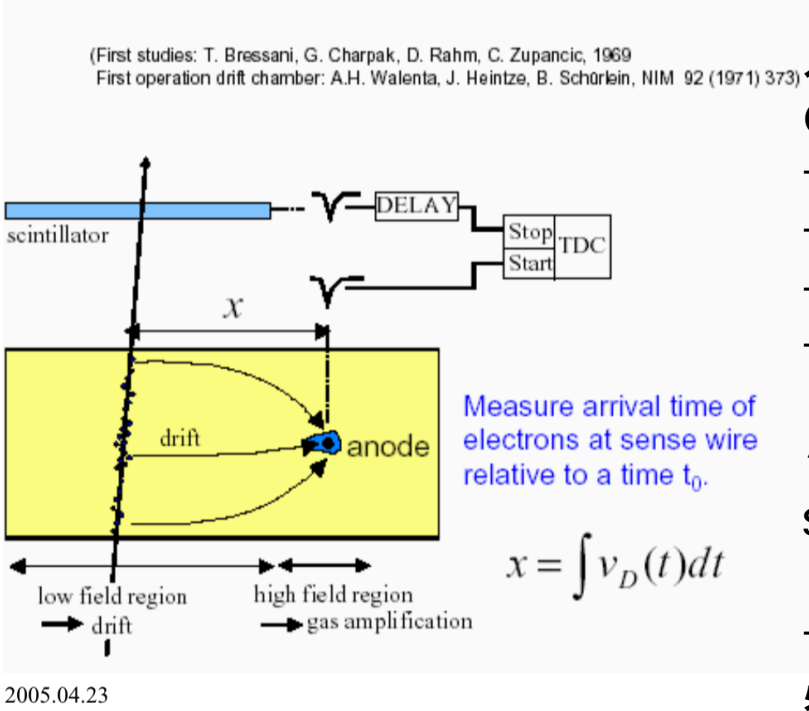
低い電圧のとき
最初のイオン対を収集する前に
再結合してしまう
①電離領域
最初のイオン対は収集できる
②比例領域
１次電離に比例した出力をする
③放電領域
増幅で生じる紫外線による
イオン化が無視できない
④Geiger領域
１次電離に関係なく一定出力
をする

ドリフトチェンバー

◎時間情報→位置情報



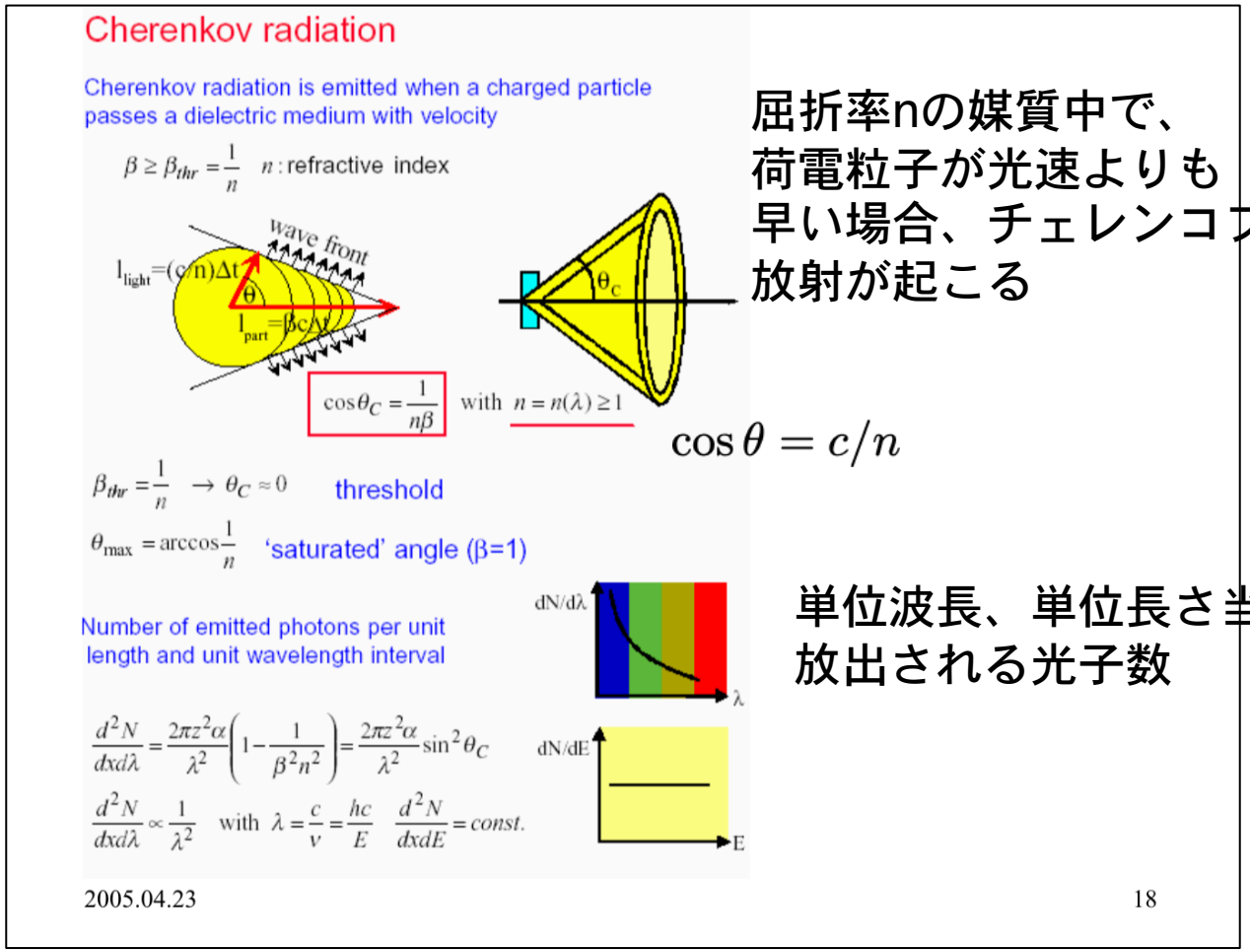
入射荷電粒子と充填ガスとの衝突
→イオン対の生成
→ドリフト
→電子雪崩により増幅
→電気信号として検出

シンチレータで観測(start)
sense wire(stop)

→ドリフト速度を知っている必要がある

チェレンコフ放射

荷電粒子が一定速度で
媒質中を走っている時の
輻射現象
→チェレンコフ放射＋
遷移放射



屈折率nの媒質中で、
荷電粒子が光速よりも
早い場合、チェレンコフ
放射が起こる

$$\cos\theta = c/n$$

単位波長、単位長さ当たり
放出される光子数

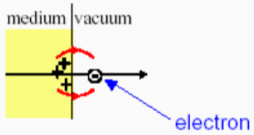
TR: 遷移放射

荷電粒子が不均一な物質中を
通過すると、光子を放出

TR predicted by Ginzburg and Franck in 1946

Electromagnetic radiation is emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

A (too) simple picture



A correct relativistic treatment shows that…

(G. Garibian, Sov. Phys. JETP63 (1958) 1079)

- Radiated energy per medium/vacuum boundary

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad \boxed{W \propto \gamma} \longrightarrow$$

Only high energy $e^{\pm}$ will emit TR. Identification of $e^{\pm}$

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \qquad \begin{pmatrix}\text{plasma}\\ \text{frequency}\end{pmatrix} \qquad \hbar\omega_p \approx 20\text{eV} \ \text{(plastic radiators)}$$

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電子の振動数

- Number of emitted photons / boundary is small

$$N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$$

Need many transitions → build a stack of many thin foils with gas gaps

境界ごとにTRの光子を
放出する確率

- X-rays are emitted with a sharp maximum at small angle

$$\theta \propto 1/\gamma$$

→ TR stay close to track

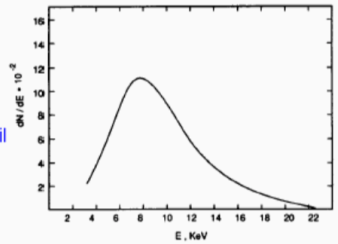
境界を増やすことが必要
X線の放射角度のピーク

- Emission spectrum of TR

Typical energy: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$

→ photons in the keV range

- Simulated emission spectrum of a CH_2 foil stack



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