Cherenkov and Transition-Radiation Detectors

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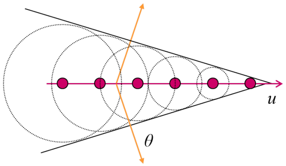
- What happens to cocenteric water waves, if duck (wave source) moves ?
  - **If the duck moves faster than the waves generated by itself, then the waves can not propagate forward from the duck, instead forming a shock front.**

Cherenkov Radiation



The Cherenkov radiation is analogous with the shock waves from a duck swimming in a pond

- When a charged particle moves inside a medium it excites the atoms and molecules of the matter and they emit radiation.
- According to the Huygens principle, the emitted waves move out spherically at the phase velocity of the medium.
- **This radiation depends on the speed of charged particle and the properties of the matter**

- If the particle motion is slow, the radiated waves bunch up slightly in the direction of motion, but they do not cross.
- **However if the particle moves faster than the light speed, the emitted waves add up constructively leading to a coherent radiation at angle θ with respect to the particle direction, known as Cherenkov radiation.**
- **The signature of the effect is a cone of emission in the direction of particle motion**

Cherenkov θ_C

For a particle with momentum p_μ, moving in a medium with refractive index n. If the radiated photon makes angle θ with the direction of propagation, then conservation of 4-momentum requires that:

$$\vec{P}_i^2 = \vec{P}_f^2 + \vec{P}_\gamma^2 - 2P_f P_\gamma \cos\theta_{p,\gamma}$$

$$E_i = E_f + E_\gamma \rightarrow \sqrt{P_i^2 c^2 + m_0^2 c^4} = \sqrt{P_f^2 c^2 + m_0^2 c^4} + h\nu$$

$$\cos\theta_{p,\gamma} = \frac{1}{n\beta} + \frac{(n^2-1)h\nu}{2P_i c n}$$

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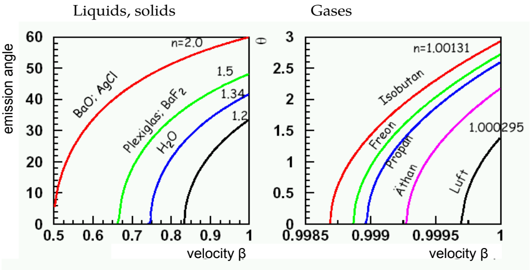
Cherenkov Radiation: Characteristics

- **There's no emission below a threshold velocity $\beta_t = \frac{1}{n}$.**
- **For relativistic particles, the Cherenkov radiation occurs at a fixed angle.**
- For non-relativistic particles There the radiation is mainly caused by the different polarization dipoles of the medium in front and back of the moving particle.
- **For dispersive mediums (refractive index varies with frequency) $\rightarrow$ the photons of different energy are scattered in various angles.**
- if the refractive index of a materials drops below 1, no Cherenkov radiation can be observed within that range.

Cherenkov Radiation



- small n is good for relativistic particles $\rightarrow$ small emission angle
- large n $\rightarrow$ large emission angle.

Cherenkov Radiation Spectrum

The number of radiation emitted dE per unit length dx per unit frequency $d\omega$ is given by the Frank-Tamm formula:

$$\frac{dE}{dxd\lambda} = \frac{4\pi Z^2 r_e mc^2}{\lambda^3}[1 - \frac{1}{n^2\beta^2}]$$

- r_e is classical electron's radius
- The emitted energy is peaked at short wavelengths(blue light)

Cherenkov Radiation Spectrum

In terms of emitted number of photos per unit length per unit wavelength:

$$\frac{dN}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}[1 - \frac{1}{n^2\beta^2}]; \quad \alpha = 1/137$$

If $n(\lambda) \approx const.$ over some range $(\lambda_i \rightarrow \lambda_f)$, then using $(\cos\theta = 1/n\beta)$

$$\frac{dE}{dx} = 2\pi^2 r_e mc^2 \sin^2\theta[\frac{1}{\lambda_i^2} - \frac{1}{\lambda_f^2}]$$

$$\frac{dN}{dx} = 2\pi^2\alpha \sin^2\theta[\frac{1}{\lambda_i} - \frac{1}{\lambda_f}]$$

Cherenkov Radiation Spectrum

In wavelength range $[350-500]nm$ (corresponding to the PMT response range). For water, with $n = 1.33; \theta_C = 41.2$

$$\frac{dE}{dx} = 1180\sin^2\theta[eV/cm] = 513[eV/cm]$$
$$\frac{dN}{dx} = 390\sin^2\theta[\gamma/cm] = 170[\gamma/cm]$$

- Cherenkov radiation is smaller than energy loss due to ionization $2MeV/cm$ and scintillation.
- Cherenkov light is emitted almost instantaneously.
- **Angular distribution of light intensity is broadened due to dispersion, energy loss of particle, multiple scattering, and diffraction.**

Cherenkov Radiation Spectrum

- The photoelectron output of a given PMT is obtained by convoluting the frequency spectrum of produced Cerenkov radiation with the frequency response of the collection system and tube.
- for the number of photons produced per unit path, we find that the number of emitted photoelectrons in the tube per unit particle pathlength is

$$\frac{dN_e}{dx} = 2\pi\alpha \int (1 - \frac{1}{n^2\beta^2})\epsilon_C(\lambda)\frac{S(\lambda)}{\lambda^2}d\lambda$$

- The number of photoelectrons is frequently written in the form

$$N_e = N_0 L \sin^2\theta$$

where L is the length of the radiator and the various efficiencies and spectral responses are incorporated in the constant N_0.

Building a Cherenkov Counter

Cerenkov radiation is very small(0.01) compared to scintillation radiation

- **The small photon yield means that the pulses from the counter are small with large fluctuations**
- In order to reduce fluctuations in the number of emitted photoelectrons (increasing the counter efficiency), the counter should be designed so that at least 20 photoelectrons are emitted per particle.
- **The Cerenkov radiator should be transparent to the emitted radiation over the desired wavelength range.**
- should not produce scintillation light.
- large index of refraction ($I \sim (1 - \frac{1}{n^2\beta^2})$)
- small density and atomic number in $\rightarrow$ minimize ionization loss and multiple scattering.
- The refractive indices of the radiator, optical grease, and PMT window should be as identical as possible

Building a Cherenkov Counter

The basic components of a Cherenkov counter are a transparent substance in which $v > c/n$; an optical system, which focuses the light; and one or more multiplier phototubes, which convert a light pulse into an electrical signal.

I) fast particle counters: the BaBar luminosity detector.

II) hadronic PID: the hadronic PID detectors at the B factory detectors—DIRC in BaBar [50] and the aerogel threshold Cherenkov in Belle

III) tracking detectors performing complete event reconstruction: large water Cherenkov counters such as Super-Kamiokande.

Cherenkov counters may be classified as either imaging or threshold types, depending on whether they do or do not make use of Cherenkov angle (θ_C) information

Cherenkov Counters with Gas Radiator

Cerenkov counters using a gas radiator are particularly useful for detecting particles with $\beta > 0.99$. The refractive indices of gases in the visible and ultraviolet range depend critically on the presence of absorption bands. The index of refraction of the gas is related to its density ρ through the Lorenz-Lorentz law

$$R = \frac{n^2 - 1}{n^2 + 2}\frac{M}{\rho}$$

Where, M is the molecular weight, R is the molecular refraction coefficient (approximately equals the volume occupied by $1 mol$ of gas, excluding the empty space).

Cherenkov Counters with Gas Radiator

Since for gases $n \approx 1$

$$n - 1 \approx \frac{3}{2}\frac{\rho R}{M}$$

For ideal gases we have $P = R' \frac{\rho T}{M}$,

$$(n-1) = (n_0 - 1)\frac{P}{P_0}$$

Where the subscript 0 indicates that the quantity is measured at atmospheric pressure.

- The threshold of a gas counter can be adjusted by varying the pressure.

For a beam of fixed velocity particles the intensity of the Cerenkov radiation varies with pressure like

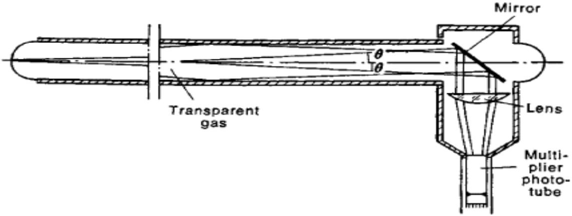
$$\cos\theta = \frac{1}{\beta\sqrt{(1 + (n_0 - 1)\frac{P}{P_0})^2}}$$

Cherenkov Counters with Gas Radiator

Table 8.3. *Properties of gas radiators, STP*

Gas	Formula	$\eta_0{}^a$ ($\times 10^{-4}$)	θ_{max} (degrees)	dN/dl γs/cm (350–500 nm)	T_{cr} (°C)	P_{cr} (atm)
Helium	He	0.35	0.48	0.027	−268	2.3
Neon	Ne	0.67	0.66	0.052	−229	26
Hydrogen	H_2	1.38	0.95	0.11	−240	13
Oxygen	O_2	2.72	1.33	0.21	−119	50
Argon	Ar	2.84	1.36	0.22	−122	48
Nitrogen	N_2	2.97	1.40	0.23	−147	34
Methane	CH_4	4.41	1.70	0.34	−83	46
Carbon dioxide	CO_2	4.50	1.72	0.35	31	73
Ethylene	C_2H_4	6.96	2.14	0.54	10	51
Ethane	C_2H_6	7.06	2.15	0.55	32	49
Freon 13	$CClF_3$	7.82	2.27	0.61	29	38
Sulfur hexafluoride	SF_6	7.83	2.27	0.61	46	37
Propane	C_3H_8	10.05	2.57	0.78	22	9
Freon 12	CCl_2F_2	11.27	2.72	0.88	112	41
Freon 114	$C_2Cl_2F_4$	14	3.03	1.09	146	32
Pentane	C_5H_{12}	17.1	3.3	1.3	197	33

Threshold Cherenkov Counter



The main characteristics of threshold Cherenkov counters is the detection efficiency.

- **A threshold Cherenkov counter should detect all particles with velocities greater than some threshold value.**
- use number of radiated photons to identify particles (useful when we don't know the composition of incoming beam)

Threshold Cherenkov Counter

Cerenkov light in the material will pass through the exit face provided that the Cerenkov angle is smaller than the critical angle. Thus, the detected particles satisfy the relation:

$$\cos^{-1}(1/n\beta) \leq \sin^{-1}(1/n)$$

The counter detects particles over a velocity range $[1/n, 1/\sqrt{n^2-1}]$

The detection efficiency of a threshold counter increases rapidly as the velocity of the incident particles.

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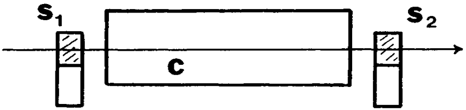
Threshold Cherenkov Counter Efficiency

Figure 8.7 A simple arrangement for measuring Cerenkov counter efficiencies. S_1 and S_2 are scintillation counters, C is the Cerenkov counter.



The Cerenkov counter efficiency:

$$\epsilon = \frac{S_1 \otimes S_2 \otimes C}{S_1 \otimes S_2}$$

The detection efficiency:

$$\epsilon(\beta) = 1 - p(0, N_e) = 1 - e^{-N_e}$$

Where $p(0, N_e)$ is the probability that no electrons were emitted by the photocathode of the PMT if the average number is N_e. (using Poisson distribution for photoelectron emission).

Threshold Cherenkov Counter

- Since $N_e = N_0 L \sin^2\theta$, therefore $\epsilon \uparrow L[N_0]$
- The shape of the efficiency curve is affected by energy loss in the gas, dispersion, and the velocity spread of the incident beam.
- The threshold velocity resolution of the counter can be determined

$$N_e = N_0 L(1 - \frac{\beta_t^2}{\beta^2}) \to \frac{\Delta\beta}{\beta} \approx \frac{N_e}{2(N_0 L - N_e)}$$

- **The behavior of the detection efficiency near threshold can be affected by the production of knock on electrons (delta rays). It is possible for a massive particle with $\beta < \beta_t$ to collide with an electron and knock it out with velocity greater than β_t.**
- **Fortunately, the delta rays are emitted with a perpendicular angular distribution**

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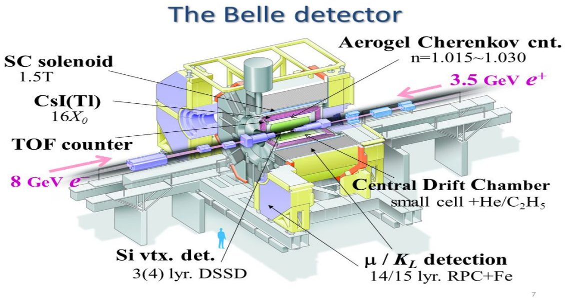
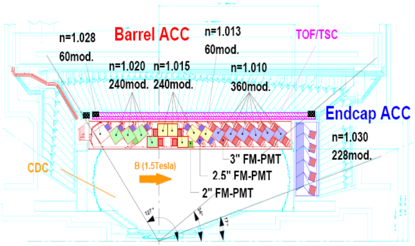
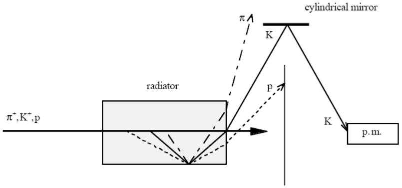
Threshold Cherenkov Counter





- Five aerogel tiles inside an aluminum box lined with a white reflector(Goretex reflector)
- Performance from test-beam

Differential Cherenkov Counter



A differential Cerenkov counter can measure the velocity of a particle by only accepting Cerenkov light in a small annulus around some angle θ.

- Using such a counter, it is possible to provide a signal for the presence of a given mass particle.
- Cerenkov light in the radiator gas is reflected by a spherical mirror. The cones of light appear to the mirror as a ring source at infinity. The image consists of a ring in the focal plane of the mirror with radius $R = f \tan\theta$

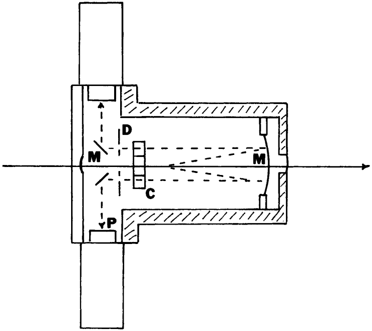
Differential Cherenkov Counter

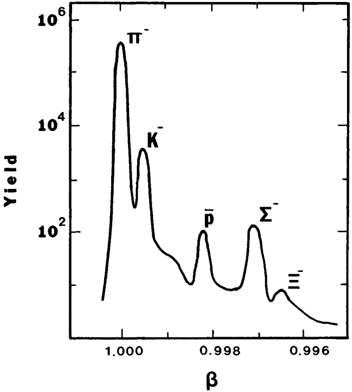
A diaphragm containing a slit of width Δr placed in front of the PMTs will only accept light from within the angular range

$$\Delta\theta = \cos^2\theta \frac{\Delta r}{f} \rightarrow \frac{\Delta\beta}{\beta} = \tan\beta\Delta\theta$$

- **The minimum obtainable angular resolution is mainly limited by dispersion.** $\Delta\theta_{disp} = \frac{\Delta n}{n\tan\theta}$
- **The angular resolution is also affected by beam divergence, optical aberrations, multiple scattering in the radiator, energy loss in the radiator, and diffraction**

Differential Cherenkov Counter

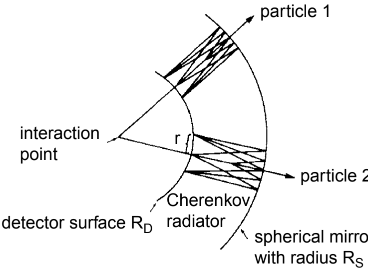




differential gas counter (DISC) used in a hyperon beam at CERN. This counter uses an adjustable optical system to correct for dispersion and geometric aberrations. A velocity resolution $\Delta\beta \sim 5 \times 10^{-5}$

The DISC counter is only suitable for use in a well-collimated beam of particles.

- **We can use the Cerenkov effect to measure the velocities of secondary particles arising from an interaction alongside with an independent measurement of the momenta to identify the particles masses.**
- **Ring Imaging Cerenkov (RICH): The radiating medium is contained between two spheres surrounding the target or intersection point. The Cerenkov light reflects off the mirror and is focused onto a ring**



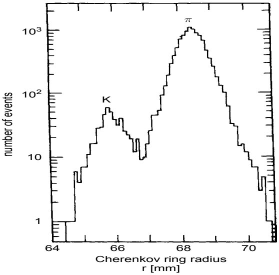
The radiator fills the volume between the spherical surfaces with radii R_S and R_D. In general, one takes $R_D = R_S/2$, since the focal length f of a spherical mirror is $R_S/2$.

- Because all Cherenkov photons are emitted at the same angle θ_c with respect to the particle trajectory pointing away from the sphere centre, all of them will be focused to the thin detector ring on the inner sphere. One can easily calculate the radius of the Cherenkov ring on the detector surface

$$r = f\theta_C = \frac{R_S}{2}\theta_C \rightarrow \beta = \frac{1}{\cos(2r/R_s)}$$

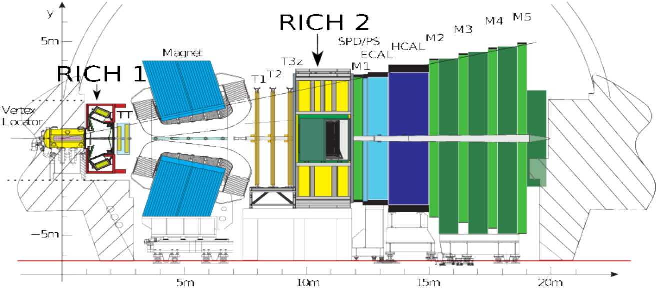
- If the momentum of the charged particle is known, then we can get it's mass from

$$p = \frac{m_0 c\beta}{\sqrt{1-\beta^2}}$$



- **The most crucial aspect of RICH counters is the detection of Cherenkov photons with high efficiency on the large detector surface.** (Multiwire proportional chambers are good choices for measuring γ coordinates).
- Distribution of Cherenkov ring radii in a pion-kaon beam at $200 GeV/c$. The Cherenkov photons have been detected in a multiwire pro- portional chamber filled with helium (83%), methane (14%) and TEA (triethylamine) (3%).
- Better Cherenkov rings are obtained from fast heavy ions, because the number of produced photons is proportional to the

Ring Imaging Cherenkov Counter: LHCb



- The Ring- Imaging Cherenkov (RICH) system is one of the key components of LHCb.
- This provides charged particle identification (π, K, p)over a wide momentum range, from $2 - 100 GeV/c$.
- It consists of two RICH detectors that cover between them the angular acceptance of the experiment, $15 - 300 mrad$ with respect to the beam axis.

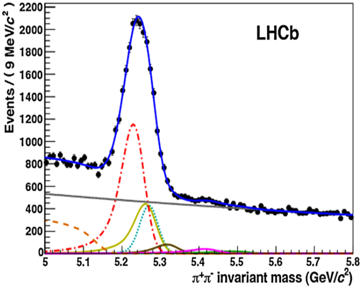


Fig. 2 Invariant mass distribution for $B \to h^+h^-$ decays [6] in the LHCb data before the use of the RICH information (*left*), and after applying RICH particle identification (*right*). The signal under study is the decay $B^0 \to \pi^+\pi^-$, represented by the turquoise *dotted line*. The contributions from different *b*-hadron decay modes ($B^0 \to K\pi$ *red dashed-dotted line*, $B^0 \to$ 3-body *orange dashed-dashed line*, $B_s \to KK$ *yellow line*, $B_s \to K\pi$ *brown line*, $\Lambda_b \to pK$ *purple line*, $\Lambda_b \to p\pi$ *green line*), are eliminated by positive identification of pions, kaons and protons and only the signal and two background contributions remain visible in the plot on the right. The *grey solid line* is the combinatorial background (Color figure online)

Transition Radiation

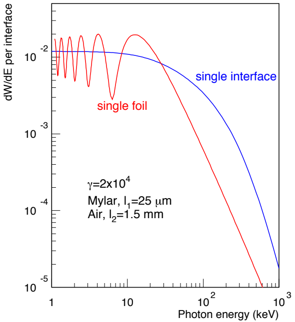
Transition Radiation (TR) happens when a charged particle moves through an inhomogeneous media (different dielectric constants)

- The energy spectrum radiated by a charged particle with a Lorentz factor γ traversing an interface between two dielectric media (with dielectric constants ϵ_1 and ϵ_2) is as following:

$$\frac{dE}{d\nu d\Omega} = \frac{\alpha^2}{\pi^2}\left(\frac{\theta}{\gamma^{-2} + \theta^2 + (1 - \epsilon_1^2)} + \frac{\theta}{\gamma^{-2} + \theta^2 + (1 - \epsilon_2^2)}\right)^2$$

- Since TR depends on γ, for a wide momentum range $(1 - 100GeV/c)$ where e^+/e^- are the only particles producing transition radiation. Kaons can also be separated from pions on the basis of TR in a certain momentum range (roughly $200 - 700GeV/c$).

Transition Radiation: in a Single Foil



A single foil has two interfaces to the surrounding medium at which the index of refraction changes. Therefore, one needs to sum up the contributions from both interfaces of the foil to the surrounding medium:

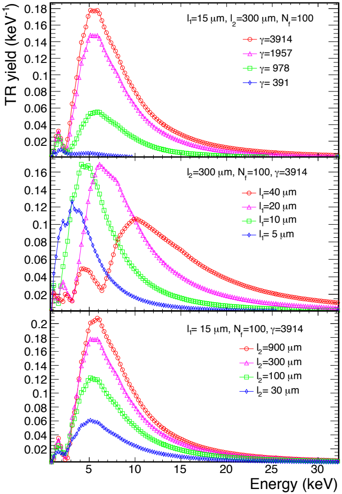
$$\frac{dE}{d\nu d\Omega}|_{foil} = \frac{dE}{d\nu d\Omega}|_{interface} \times 4\pi \sin\theta_1/2$$

Since the emission probability for a TR photon in the plateau region is of order α/π per interface. For this to lead to a significant particle discrimination one needs to realize many of theses interfaces in a single radiator.

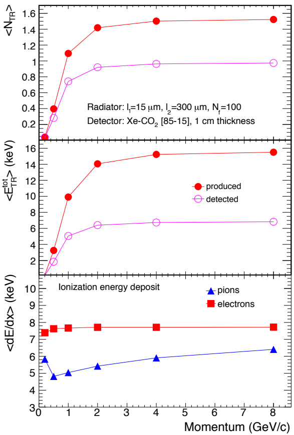
Transition Radiation: Spectrum

TR production as a function of: the Lorentz factor γ (upper panel, corresponding to an electron momentum of $0.2, 0.5, 1 and 2 GeV/c$), foil thickness l_1 (middle panel) and foil spacing l_2 (lower panel).

- TR is very useful in the X-ray range, which is why Xe detectors are popular
- While Cerenkovs discriminate on beta, TRDs are sensitive to gamma, so they are complementary

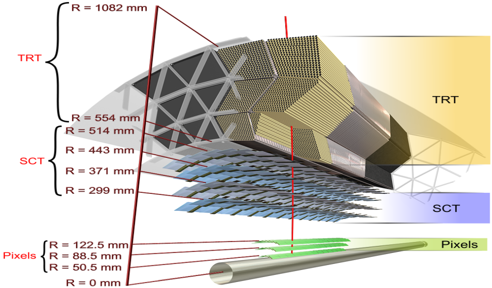


Transition-Radiation Detectors



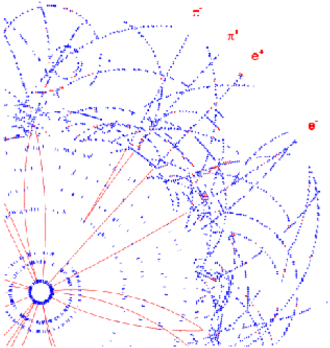
- Due to the very small TR emission angle, the TR signal generated in a detector is overlapping with the ionization due to the specific energy loss dE/dx and a knowledge (and proper simulation) of dE/dx.
- due to the large tails in the energy loss spectrum for pions, the detector has to have many layers. In case the full charge signal is available the discrimination is done using either a normal mean, a truncated mean.
- **There are two main types of TRDs: differential like ATLAS, and total energy measurement like Hermes**

Transition-Radiation Detectors



- The ATLAS transition-radiation tracker (TRT) is the largest present-day TRD detector.
- The TRT is part of the ATLAS inner detector and it is used both for charged-particle tracking and electron/pion separation. It consists of 370000 cylindrical drift tubes (straws). Made from kapton and covered by a conductive film, the straw tube serves as cathode of a cylindrical proportional drift counter.
- A central $30\mu m$-diameter gold-plated tungsten wire serves as anode. The layers of straws are interleaved with polypropylene foils or fibres working as radiator. The tubes are filled with a gas mixture.

Transition-Radiation Detectors



A simiulated $B_d^0 \to J/\psi(\to e^+e^-)K_s(\pi^+\pi^-)$

- The electron/pion separation is based on the energy deposition.
- A typical energy of the transition-radiation photon in the TRT is $8 - 10keV$, while a minimum-ionising particle deposits in one straw about $2keV$ on average
- As separation parameter the number of straws along the particle track having an energy deposition exceeding a certain threshold can be defined.

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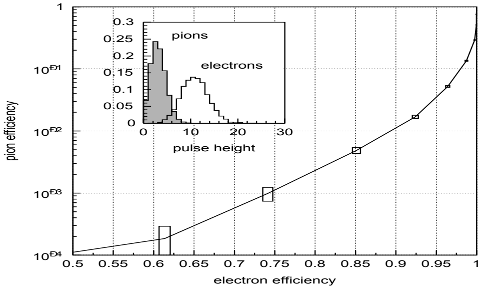
Transition-Radiation Detectors



Electron/pion separation capability measured with a prototype. The insert shows the energy depositions in a single straw for pions and electrons.