Particle Identification and Energy Measurement at High Energies

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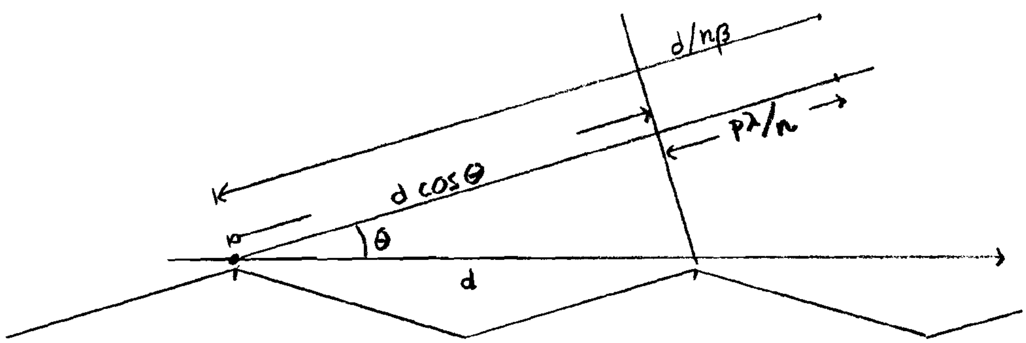
1. Electromagnetic Radiation

We consider the case where

$$\beta\to 1 \quad , \quad \text{e.g.} = \beta = 0.9999999.$$

Therefore, we need an interferometric method to compare βc with c. When we think of interferometers, we think of gratings. So did Purcell (Smith and Purcell, Phys. Rev. 1953, p. 1069). The sketch shows a particle travelling parallel to the surface of a grating in a medium with index of refraction n.



The condition for constructive interference of order p is

$$p\frac{\lambda}{n} = \frac{d}{n\beta} - d\cos\theta .$$

For p = n = 1

$$\cos\theta = \frac{1}{\beta} - \frac{\lambda}{d}$$

or

$$\theta^2 \simeq \frac{2\lambda}{d} - \frac{1}{\gamma^2} \qquad (1-\beta \simeq \frac{1}{2\gamma^2}).$$

A dipole e oscillates $1/\alpha$ times to make one photon per octave.

To have θ sensitive to γ, we need $\gamma^2 \sim \lambda/d$. Then, we get a yield of photons

$$\frac{dN}{dx} = \frac{\alpha}{d} \cong \frac{\alpha}{\gamma^2\lambda} \qquad \text{per octave per cm.}$$

Compare the above with the case for which $p = 0$ and $n>1$, Cerenkov radiation

$$\cos\theta = \frac{1}{n\beta}$$

$$\frac{dN}{dx} = \frac{d}{\gamma^2\lambda} .$$

This is the same result. In this way, Purcell (1961) concluded that a grating interferometer has no advantage over a Cerenkov interferometer. But this is not quite right; Garibian (1961) pointed out that a grating also works with x-rays, where $n<1$, even if the particle passes through the grating material

For a Cerenkov radiator with $\lambda \approx 10^{-5}$ cm, we need ~50 photons. For an x-ray radiator with $\lambda \approx 10^{-8}$ cm, we only need ~10 photons. Overall the x-ray radiator is shorter by a factor of 5000.

A practical grating is made of foils ("transition radiation"). We want $Z \sim 1$, since absorbtion goes as $Z^{3.5}$. We have to consider the effect of n:

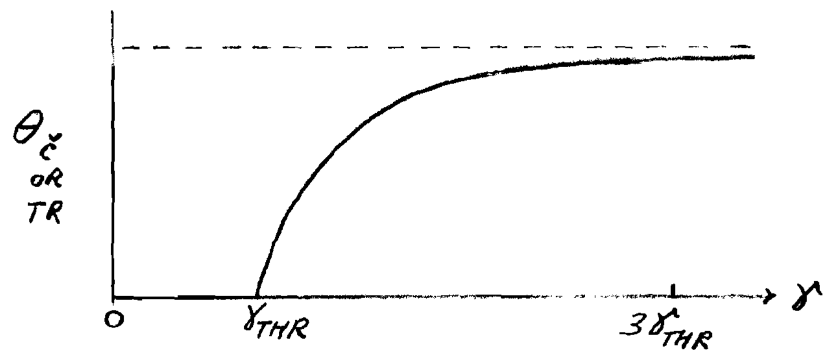
$$n = 1 - \frac{\omega_o^2}{\omega^2} \qquad (\omega_o \sim 10 \text{ eV}).$$

In order that the interferometer be sensitive to $1/\gamma^2$, we need $1-n \sim 1/\gamma^2$; therefore

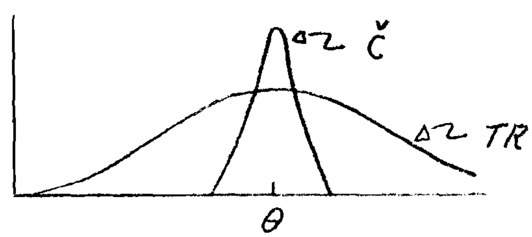
$$\omega \sim \gamma\omega_o .$$

For $\gamma = 10^3$, $\omega \sim 10$ keV, which is all right. But $\gamma = 10^2$ implies $\omega \sim 1$ keV - a bad region in which to work.

The formula we have given is for a threshold detector, Cerenkov or TR. A differential detector measures θ - "ring imaging".



If we measure θ to 1%, we can distinguish $3\gamma_{THR}$ from ∞. The effective threshold is 3 times higher, but the $\frac{dN}{dx}$ is 3^2 times greater than a detector with γ_{THR} raised by 3. However, we need more photons to define the ring, and the length required is perhaps reduced by a factor of 3. If the radius can be determined with higher precision as in the DISC counters, the length required is reduced still more. In TR, the ring is fuzzy because of broad bandwidth used, and strong variation of n:



The θ measurement requires no more photons, rather fewer, because of the elimination of the signals due to the track itself, and the advantage in length is again ~3.

Note also that π-e separation requires radiation from the e be detected efficiently, but K-π etc. separation over an appreciable momentum band requires dealing with π near threshold giving fewer photons and K's just above threshold, giving a few photons. This requires more length for a threshold detector.

The Cerenkov picture is summarized in Figure 1 by giving the length L required for identification of particles with a given γ. We include a line for the DISC type which determines $\Delta R/R$ with high precision, but requires a highly collimated particle beam. Devices with moderate solid angle, such as spot focusing detectors, can be built with lengths in between DISC and ring imaging detectors.

Similar details affect TR detectors. Here one has a choice of keeping the photon bandwidth at ~10 keV, convenient for PWC Detection, or allowing it to grow with γ. The latter is more natural from the radiator design aspect, and leads to an L which grows only $\propto\gamma$. The former requires special foil fabrication to lower the foil density, and thus ω_0, and gives $L\propto\gamma^2$.

As γ is lowered below 1000, severe problems are encountered:

The photon energy falls and self absorption in the radiator becomes important.

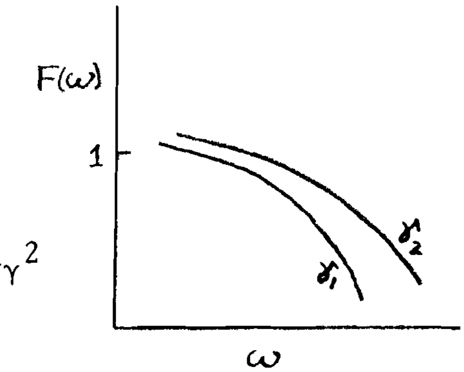
The foil thickness becomes just a few microns, but it is more important than ever to use a low Z material.

A very practical radiator can be made with 30 μm lithium foils, 20-40 cm thick, giving ~10 photons for γ = 3000. These have been used for electron detection at the ISR, the SPS Y-beam, and the BNL-MPS. An Aachen-BNL-CERN-Moscow collaboration is now attempting to make a γ = 600 radiator based on 50 cm of 3 μm Li-H dust, with a volume fraction 10%. Calculated performance is shown in Figure 2.

For $\gamma \lesssim 10^4$, the TR radiator may not be the optimum choice. Consider synchrotron radiation:

$$\frac{dN}{dx} = 1.2H \frac{d\lambda}{\lambda} F(\omega) \quad \text{per meter}$$

where H is in Tesla and $F(\omega)$ is of order unity below a cutoff.



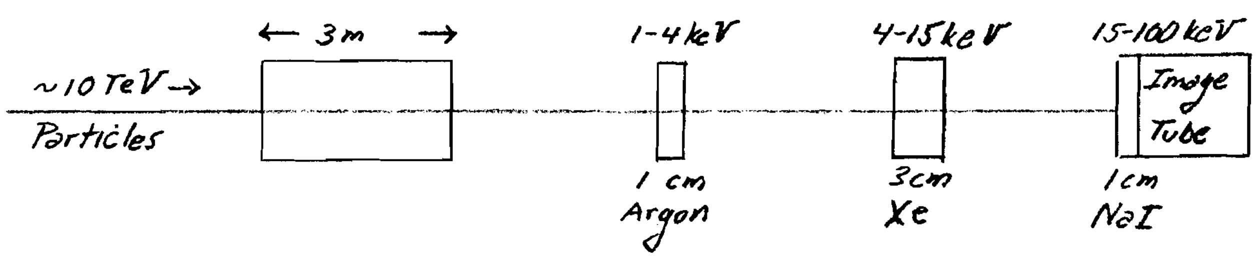
$$R \equiv \frac{\text{synchrotron radiation}}{\text{transition radiation}} = \frac{1.2}{\alpha} H ƛ \gamma^2$$

$$= 1 \text{ at } \gamma_s = \sqrt{\frac{\alpha}{1.2} \frac{1}{ƛ}} \ .$$

For $\omega_{T.R.}$ = 10 keV and H = 1 Tesla, γ_s = 20,000. Most important - note that dN/dx does not depend on γ! If we take H = 3T, then L - 3m produces 10 photons for $\gamma = 10^4$ up to ∞.

The other detectors depend on γ only, but for synchrotron radiation, we must consider the mass as well, to make sure that $E_{crit}(\text{eV}) = .9\times10^{-4} \frac{\gamma^2 H}{m}$ (T, MeV) is in a detectable range, say >1 keV. π's at γ_s are ok (x-rays), k's at $\gamma = 10^4$ give radiation which is too soft, unless H is $\gtrsim$ 6T. (The optical region is not attractive with present technology.)

A detector would look like this:



The combination of the three spectral detectors will allow k/π/p separation above 3 TeV, up to ~50 TeV!

It will be noted that there is a gap in the γ coverage of the detectors described so far $200 \lesssim \gamma \lesssim 600$, at least for large solid angle coverage (a DISC can go to $\gamma = 600$). If we want to do the job in ~1 m, our general dimensional scaling laws developed at the beginning of this paper suggest we should use photons $\omega \gtrsim \gamma\omega_0$ ~few hundred eV. But in this energy region,

(1) n varies wildly,

(2) there is very strong absorbtion.

It is therefore impossible to make an interferometer with transmission through matter in this region.

Gratings in vacuum could be used. No practical method has been suggested. Something cruder must be done. The "production" of virtual photons in this (100 eV) energy range is increasing linearly with energy; this interacting with an exponential tail of the atomic wave function, produces a $\ell n\ \gamma$ rise in ionization. This is weak compared to the threshold shapes ($\sqrt{\gamma^2-\gamma_0^2}$) of our interferometers, but this is to be expected.

Furthermore, the ionization distribution is fluctuating in a strongly non-gaussian manner. Many (~200) samples are required, to achieve sufficient measurement accuracy. To carry that out in a small L, allowing 10-20 primary ionizations/sample, one pressurizes the gas. But polarization in a dense gas shields the field and cuts off the increase at large distance, i.e. large γ. The L required goes as

$$L \propto (\gamma_{max})^2.$$

We now summarize all this in Figure 3.

2. Calorimeters

The length of a calorimeter scales as ℓnE, leading to the following table

length (m)		E	
		10 GeV	10 TeV
material	F_e	2	4
	U	1	2

Regarding hadron energy resolution, three contributions should be noted:

(a) Sampling: if $\sigma \propto E^{-\frac{1}{2}}$, then for Fe with 1.5 mm plates, $\sigma \sim 8\%/\sqrt{E_{GeV}}$. At 10 TeV, the energy resolution would be ~0.08%!

(b) Binding Energy Fluctuations: (see Figure 4)
This effect probably leads to resolution scaling according to

$$\sigma \propto \frac{1}{E^{\frac{1}{2}} \ \ell n E}$$

and may be important.

(c) Technical limits:

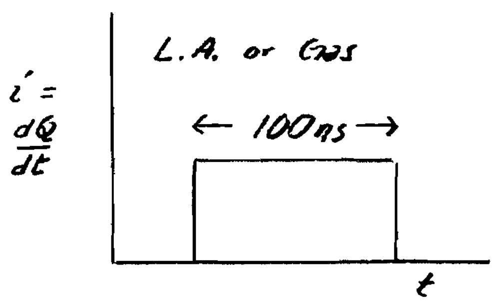
(i) Photomultiplier tubes ~1-2%
drift
rate effect
uniformity

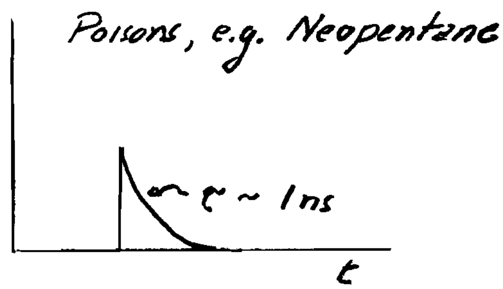
(ii) Ion chambers - 0.1-0.2%
liquid argon
gas
other

(iii) Radiation damage
scintillator dies after $\sim 10^6$ rads,

Outlook: The ℓnE term may be important in Fe; in U_{238}, the binding energy is already down to 25%/$\sqrt{E}$. It could be that $\sigma_{Hadron} \sim \sigma_{sampling}$ at 10 TeV, even in Fe. We need measurements at 400 GeV. In any case, the "technical limits" probably dominate.

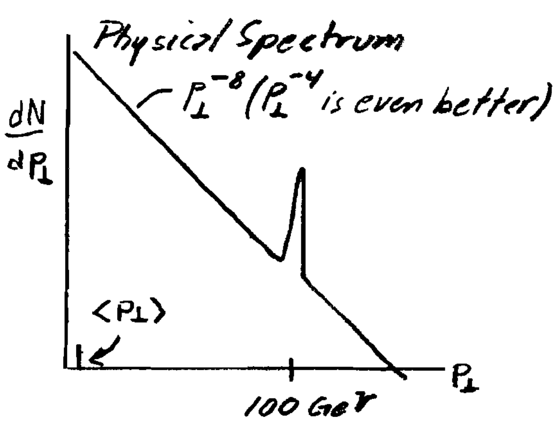
Consider the rate limitations. It's hard to get below 20-30 ns with the scintillator - photomultiplier combination. In ion chambers, either gas or liquid argon, the collection time is ~100 ns. But, as a new idea, how about the use of highly poisoned liquids? Typical current signals might appear as sketched below.

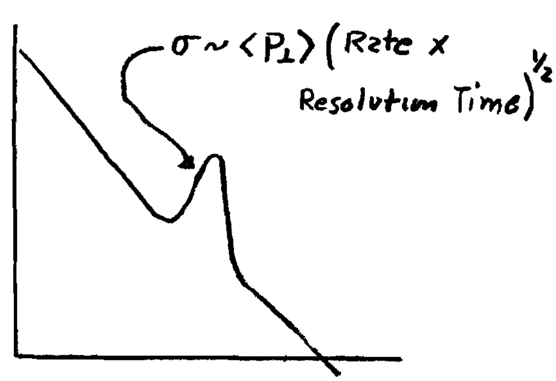




In the poisoned case, Q is down by ~100, but that is ok for the TeV range.

Can calorimeters work with pile-up? (See "Impactometer" 1971). We are measuring power laws; pile-up produces Gaussians.





If the rate is $\sim 10^{10}$ Hz and $\tau \sim 10$ ns, then $\sigma \sim 3$ GeV, which is ok.

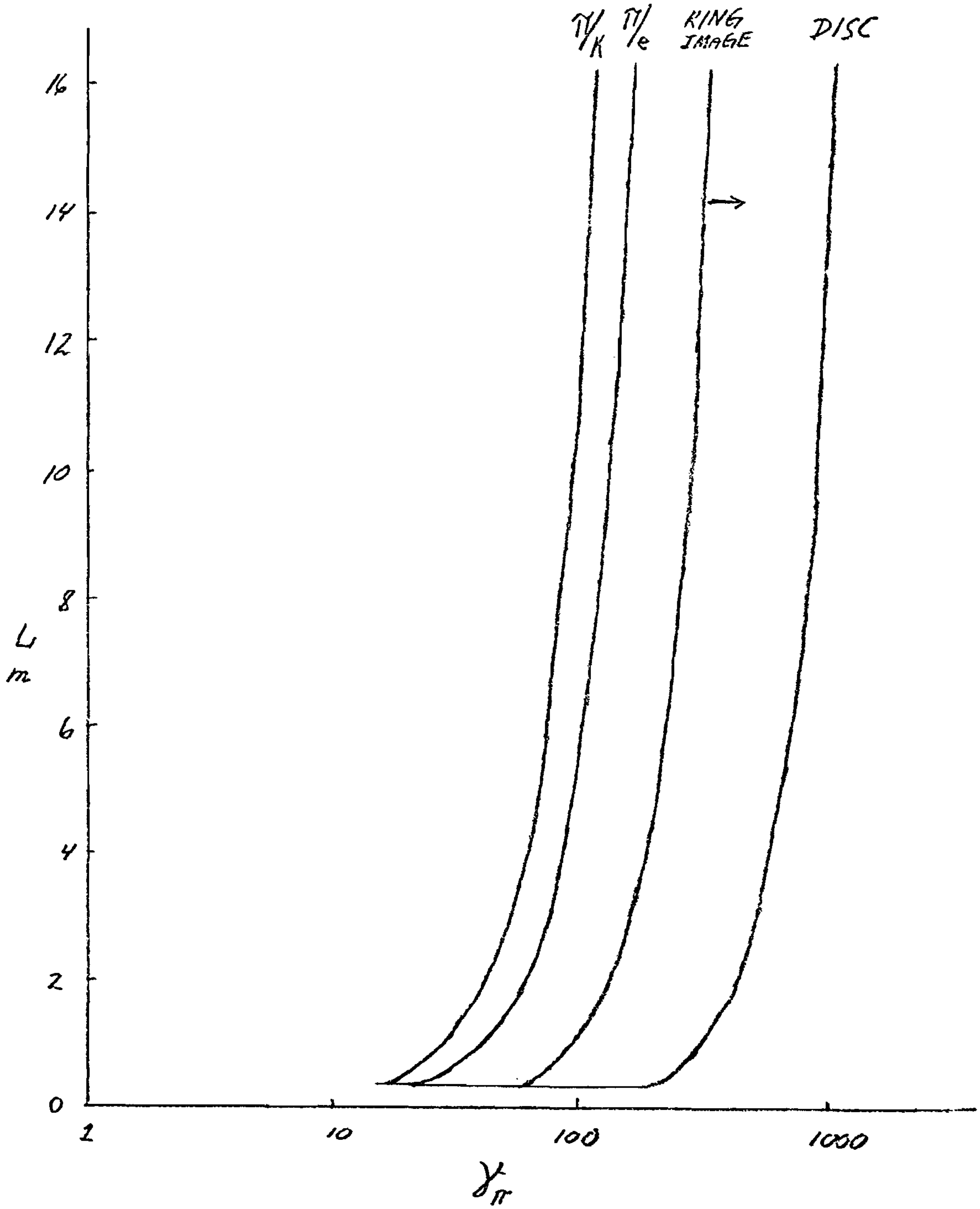
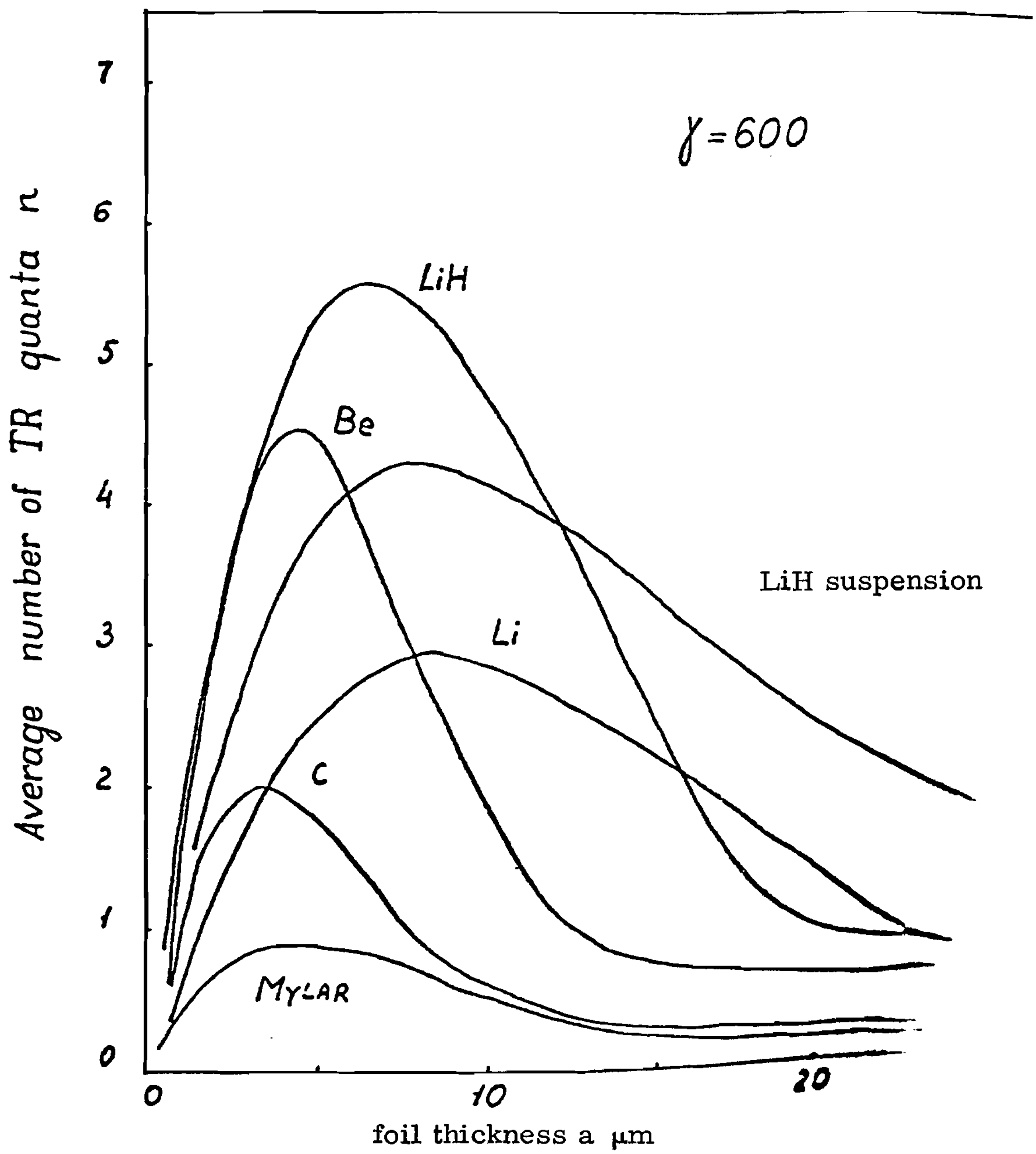


Fig. 1



γ=600
Average number of TR quanta n
7
6
5
4
3
2
1
0
LiH
Be
LiH suspension
Li
C
MYLAR
0
10
20
foil thickness a μm

Fig. 2

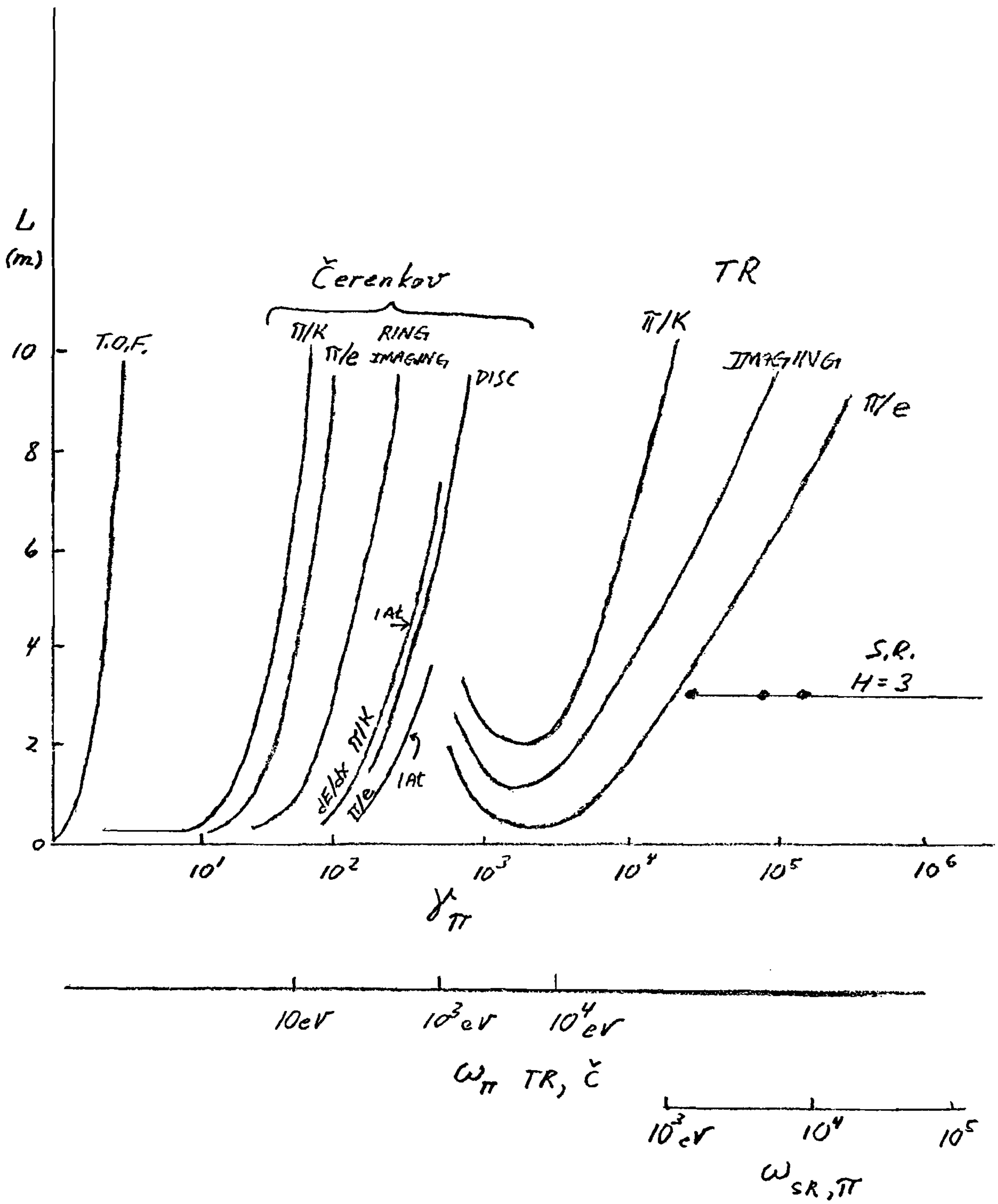

L
(m)
Čerenkov
TR
T.O.F.
π/K
π/e
RING
IMAGING
DISC
π/K
IMAGING
π/e
1At
dE/dx π/K
π/e
1At
S.R.
H = 3
0
2
4
6
8
10
10^1
10^2
10^3
10^4
10^5
10^6
γ_π
10eV
10^3eV
10^4eV
ω_π TR, Č
10^3eV
10^4
10^5
$\omega_{SR,\pi}$

Fig. 3