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INTERACTIONS BETWEEN $e^{\pm}$ BEAMS AND INSTRUMENTATION IN THE SPS TRANSFER LINES

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I. INTRODUCTION

Interacting with matter of any interceptive instrumentation like Secondary Emission Monitors (SEM), the $e^{\pm}$ beams lose energy mainly by two processes : - ionisation (collision with atomic electron)
- radiation (Bremsstrahlung)

and are deflected by Coulomb elastic scattering.

Other effects like nuclear interactions are also possible with high energy beams but their perturbation either on the beam or on the equipment can be neglected.

An interceptive device can also be perturbated by effects produced in its vicinity such as

- synchrotron radiation in an upstream bending magnet.
- photons produced by Bremsstrahlung in an other foil.

The high energy photons produced by these effects will also interact with matter by three processes :

- photo electric emission
- compton effect
- pair production

The aim of this note is to evaluate how the beam is pertubated by the SEM and how the secondary effects due to the beam affects the quality of the measurement.

II. IONISATION EFFECTS

The average loss of $e^{\pm}$ per unit length due to Coulomb interactions can be written as follows 1).

$$\frac{dE}{dx} = -\,2C\,m_o c^2 \left|\,\mathrm{Ln}\,\frac{(\pi m_o c^2)^2}{(1-\beta^2)^{3/2}\,I^2(z)} - a\,\right|$$

where

$m_o c^2$ = electron rest energy = 0.511 Mev

$C = 0.150\,\frac{Z}{A}\quad cm^2\,g^{-1}$

with Z,A = atomic number and mass of the target

β = relative $e^{\pm}$ velocity

I = ionisation potential

$$a = \begin{cases} 2.9 \text{ for } e^- \\ 3.6 \text{ for } e^+ \end{cases}$$

Example : SEM with aluminium foils

Al $Z = 13$ $A = 27$ $I = 150eV$ ρ = density = $2.7 g\ cm^{-3}$

$\gamma = (1-\beta^2)^{-1/2} = 6850$ for $e^{\pm}$ at 3.5 GeV

$-\frac{dE}{dX} = 3.05$ Mev $g^{-1}\ cm^2$ with $dX = \rho\ dx$

For a total thickness of $\Delta x = 0.1mm$

$\Delta E = \rho\ \Delta x\ (\frac{dE}{dX}) = 8.25\ 10^{-2}$ Mev.

$$\frac{\Delta E}{E} = \frac{8.25 \times 10^{-2}}{3.5 \times 10^{+3}} = 2.3 \times 10^{-5}$$

1) "High energy particles", B. Rossi

III. RADIATION EFFECTS (Bremsstrahlung)

For high energy $e^{\pm}(\gamma>40)$, the average loss per unit length due to Bremsstrahlung is proportionnal to energy and given by [1)]

$$\frac{dE}{dx} = -4\alpha \frac{N}{A} Z^2 r_e^2 E \left| \mathrm{Ln}\,(183\, Z^{-1/3}) + \frac{1}{18} \right| = -\frac{E}{X_o}$$

Where

$\alpha = \frac{e^2}{hc} = \frac{1}{137}$

N = Avogadro's number = 6.02×10^{23}

r_e = electron radius = $0.281\ 10^{-12}$ cm

E = $e^{\pm}$ energy

X_o = radiation length

Example : SEM with aluminium foils

$X_o = 26.3$ g cm^{-2}

$$\frac{dE}{dx} = -\frac{E}{Xo} \dashrightarrow \frac{dE}{E} = -\frac{dX}{Xo}$$

For a foil of thickness $\Delta x = .1$mm $\Delta X = \rho\Delta x = 2.7 \times 10^{-2}$ g cm^{-2}

$\frac{\Delta E}{E} = 10^{-3}$

The radiation losses are two orders of magnitude higher than the ionisation losses.

As a consequence, when introducing all position monitors in the beam (as done at present) for beam steering or checking, beam oscillation will occur due to the energy offset in the beam. For instance in TI18 [2)], the difference of the beam trajectories depending whether the 9 monitors needed for beam steering are in or out leads to a displacement of 29 mm and an angle of 0.27 mrad at the LEP injection point.

2) "Mesure de la position transversale des faisceaux $e^{\pm}$"
SPS/ABT/SP/Tech. Note/85-01 - 18/1/85
S. Peraire, N. Siegel, E. Weisse

The $\Delta E/E$ per monitor may be decreased by making large enough holes in the bias foils (so that the beam passes unhindered) and (or) using thinner foils. However, even if one obtains an improvement by a factor of 4, this would be insufficient $^{2)}$.

Similar effects will occur in TI12, TT10 and TT70. The consequence is that beam steering in the usual way as for protons with the SEM monitors (i.e. all monitors in, checking or steering, then all monitors out) cannot be applied for e^+, e^- beams.

IV. BEAM BLOW UP DUE TO COULOMB ELASTIC SCATTERING

The projection of the mean square angle of scattering on the plane containing the initial trajectory is given by $^{1)}$

$$<\theta^2> = \frac{1}{2} \left(\frac{E_s}{p\nu}\right)^2 \frac{\Delta x}{X_o}$$

where :

E_s = constant = 21 Mev

ν = particle velocity

p = momentum of the incoming particle in Mev/c

Δx = thickness ($=1*10^{-2}$ cm for a SEM)

X_o = radiation length (=9 cm for Al)

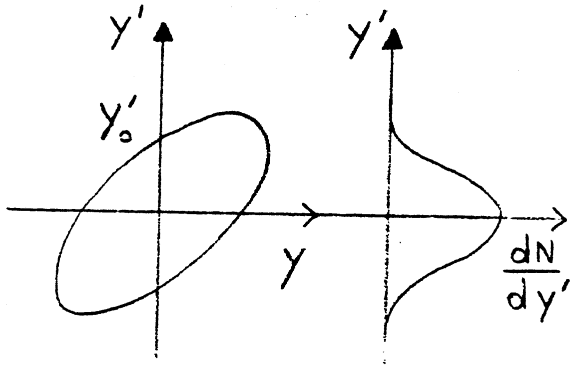
then :

$<\theta> = 0.1$ mrad for a 3.5 Gev beam.

The result is an emittance blow-up, $\Delta\varepsilon$, usually defined at $Y_o' = 2<\theta>$

$\Delta\varepsilon = \beta Y_o'^2 = 4\beta<\theta>^2$

β being the betatronic amplitude.



In TT10 and TT70 at 3.5 Gev, the SEM's are currently put at $\beta \simeq 60$m, then $\Delta\varepsilon = 4\beta \langle\theta^2\rangle \simeq 2.4\pi$ mrad x mm which is greater than the expected $e^\pm$ emittances at 3.5 Gev by one order of magnitude ($\varepsilon_H = 0.65\pi$, $\varepsilon_V = 0.65\pi$)

In TI12 and TI18 at 20 Gev the effect is reduced by
$(\frac{3.5}{20})^2 = 3x10^{-2}$
but is still of the order of the expected beam emittances
($\varepsilon_H = 0.1\pi$, $\varepsilon_V = 0.1\pi$)

If several SEM's are put together into the beam along a transfer line, the effect is cumulative, leading to unacceptable blow-up.

V. SYNCHROTRON RADIATION EFFECTS

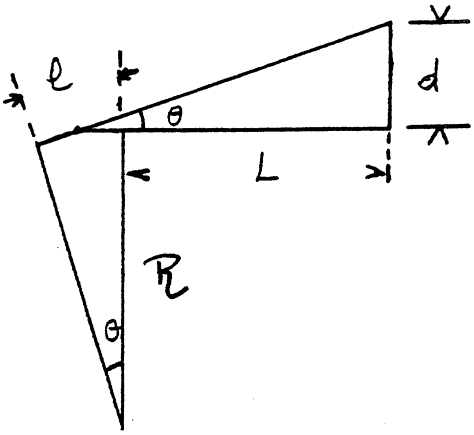
In bending magnets upstream of a monitor synchrotron radiation is emitted by $e^\pm$ beams, having the following consequences :

a) The photon flux emitted tangentially to the trajectory hits an interceptive monitor (SEM) non symmetrically relative to the beam. The secondary e^- produced by the interaction between photons and matter can perturb the measurement

b) A SEM consisting in a serie of thin foils (typically each horizontal or vertical detector is inserted between 2 bias foils), the incoming high energy photons, slightly attenuated by the upstream foil, can also perturb the dowstream foils. Furthermore the secondary e^- created in the upstream foil can be trapped by the dowstream one

c) In a similar manner, photons having hit the vacuum chamber upstream of the detector can produce forward e^- coming onto it.

5.1 Photons intercepted by a SEM



Length of synchrotron radiation emission

A SEM of semi aperture d intercepts the photons emitted by synchrotron radiation in a bending magnet of curvature radius R over a length l such as for small angles :

$$l = R\theta = R\ \frac{d}{L+l/2}$$

L = distance between the magnet output and the SEM.

The worst case for synchrotron radiation is obtained in TI18 by the magnet IMAT 180322 followed by the SEM IBGH 180416 with

$R = 60.2\mathrm{m}$ $L = 8.86\mathrm{m}$ $d = 0.07\mathrm{m}$

One finds $l = 0.45\mathrm{m}$ $\theta = 7.5\mathrm{mrad}$

Number of photons

The total photon flux is given by 3)

$$\frac{d^2N\gamma}{dsdt} = 1.28{*}10^{17}\ \frac{E(GeV){*}I(mA)}{R(m)}$$

for particles of energy E and intensity I

If N particles travel in ΔT the magnet length l

$$I(mA) = \frac{N{*}e}{\Delta T} \times 10^{3}\ (e = 1.6{*}10^{-19}C)$$

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3) "Synchrotron Radiation" Sokolov, Ternov

The total number of photons is

$$N_\gamma = 1.28 \times 10^{17} \times 1.6 \times 10^{-16} \frac{E(GeV)N}{R(m)} \times 1_m$$

$$\frac{N_\gamma}{N} = 20.5 \frac{E(GeV)}{R_m} \times 1_m$$

In the previous example at 20 GeV with R = 60.2m 1 = 0.45m

$$\frac{N_\gamma}{N} = 3.06$$

5.2 Photon spectrum

The synchrotron radiation spectrum is quite large and can be defined by a universal function (Fig.1) versus the ratio λ/λ_c where λ_c is the critical wavelength

$$\lambda_c = \frac{2\pi R}{3\gamma^3}$$

For $E = 20$ GeV $\gamma \simeq 4 \times 10^4$ $R = 60.2\text{m}$

$\lambda_c \sim 2 \times 10^{-12}\text{m} = 0.02$ Å

and E_c = critical energy = $h \frac{c}{\lambda c}$

h = Planck's constant = 6.62×10^{-34} J.S

c = light velocity = 3×10^8 m

$E_c = 10^{-13}\text{j} = 0.62$ MeV

By definition half the total power is radiated above the critical energy and half below.

5.3 Photon attenuation in matter

The total X-ray attenuation (scattering + photo electric + pair production effects) is defined by the number N of photons escaping from a target of thickness x bombarded by No photons [4]

$$N = No\ e^{-\mu x}$$

where μ is the linear attenuation coefficient.

The mass attenuation coefficient $\frac{\mu}{\rho}$ (ρ = density) is given in table I for Aluminium [5]

The number of high energy photons ($\geq E_c$) $\frac{\mu}{\rho} \leq .0777$ passing through a SEM ($x = 10^{-2}$cm)

$$N = N_o\ e^{-0.0777 * 2.7 * 10^{-2}} = .998\ N_o$$

is hardly modified giving negligible perturbations.

For low energy photons in particular nearly the K shell energy (~1.5 Kev for Al) the attenuation is very large due to the photo electric emission. For instance at 10 Kev N_o is attenuated by

$$N = N_o\ e^{-26.3 * 2.7 * 10^{-2}} \simeq 0.5\ N_o$$

The attenuation mainly corresponds to electron production by photo electric or Compton effects - Electron recombination occurs in matter in such a way that only a smaller quantity of e^- escapes from the surface, e^- in the forward direction being always in greater quantity than in the backward direction (Fig.2) [6]

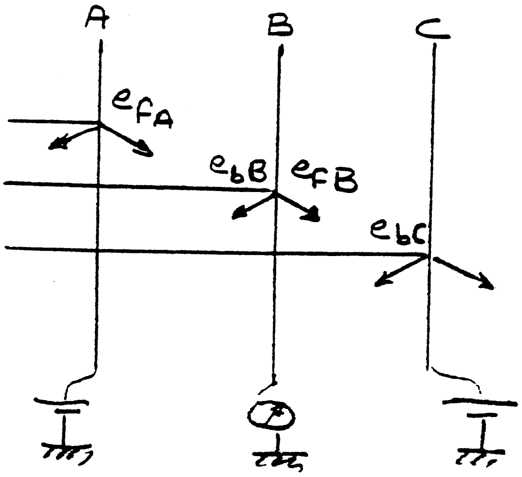
The average quantum efficiency for Al below E_c(=0.6Mev) is less than $1 * 10^{-3}$ e^-/incident photon

4) "X-rays in atomic & nuclear physics". NA DYSON - Longmann editor

5) "X-ray attenuation coefficients" B. Grodstein - N.B.S editor

6) "Second analytical photo-Compton current methods"
TA Dellin et al, IEEE NS-22, N°6, Dec. 75

In a typical SEM configuration the measuring foil B is surrounded by 2 positively charged bias foils A and C.



Without bias voltage, B gets photo and compton e^- from A (e_{fA}) and B (e_{bC}) and sends e^- to A (e_{bB}) and to C (e_{fB}), the net result being :

$$e^-_{fA} - e^-_{bB} - e^-_{fB} + e^-_{bC} = 0$$

With a bias voltage V, only the e^-_{fA} and e^-_{bC} emitted with an energy > eV can reach B, the net result being :

$$(e^-_{fA} + e^-_{bC}) - (e^-_{fB} + e^-_{bB}) < 0$$

The maximum could be reached if all $e^-_{fA} + e^-_{bC}$ are recaptured and its value would be ~ 1×10^{-3} of the incident photon flux. Remembering in the case of IMAT 180209 that the synchrotron radiation hits the outside part of the detector IBGH 180416 with the ratio

$$\frac{N_\gamma}{N} = 3.06$$

the foil B ($e_{bB}+e_{fB}$) could emit 3.06×10^{-3} e^-/incident particle, to be compared with 5×10^{-2} e^-/incident particle produced by the secondary emission effect.

Therefore a perturbating effect of less than 8% could be obtained in the position and profile measurements due to synchrotron radiation. But numerical calculation and experiments have to be done to get a better approximation. Anyway when possible it is worth putting such a detector as far as possible from the synchrotron radiation source.

The photons produced by Bremsstrahlung in the upstream foil A hit the foil B with a symmetrical configuration according to the beam. Even if they contribute to enhance the apparent secondary emission coefficient relative to a proton beam, they will not perturb a position or profile measurement.

The photo or compton e^- produced by synchrotron radiation hitting the vacuum chamber upstream of the detector are considered to be low energy e^- with a random distribution in angle; therefore they will be mainly absorbed by the first bias foil or if not they will add noise to position or profile measurement.

VI. CONCLUSIONS

The steering of a transfer line consisting in introducing all the SEM position monitors simultaneously into the beam, as it is done for high energy protons can not be used for $e^\pm$ beams due to the energy loss by Bremsstrahlung and to the beam blow-up by Coulomb scattering.

For the same reasons the transverse profile measurement will also be strongly pertubated if more than one monitor intercepts the beam at a time. Even the synchrotron radiation produced upstream of a profile monitor could slightly perturb the measurement.

It is then recommended to use as much as possible non interceptive monitors such as directionnal couplers for beam position measurement. For profile measurement, one SEM grid at a time can be put into the beam, providing the monitor is not locate just after a strong bending magnet.

An effort should be made in order to reduce the effective mass of the secondary emission monitors mainly in the tranfer lines common to leptons and hadrons (TT10, TT70) while ideally non interceptive profile measurement by detecting the synchrotron radiation should be the best method for e^+e^- tranfer lines.

Distribution :

Personnel Scientifique et Technique SPS

TABLE 1

TABLE 19. Aluminum

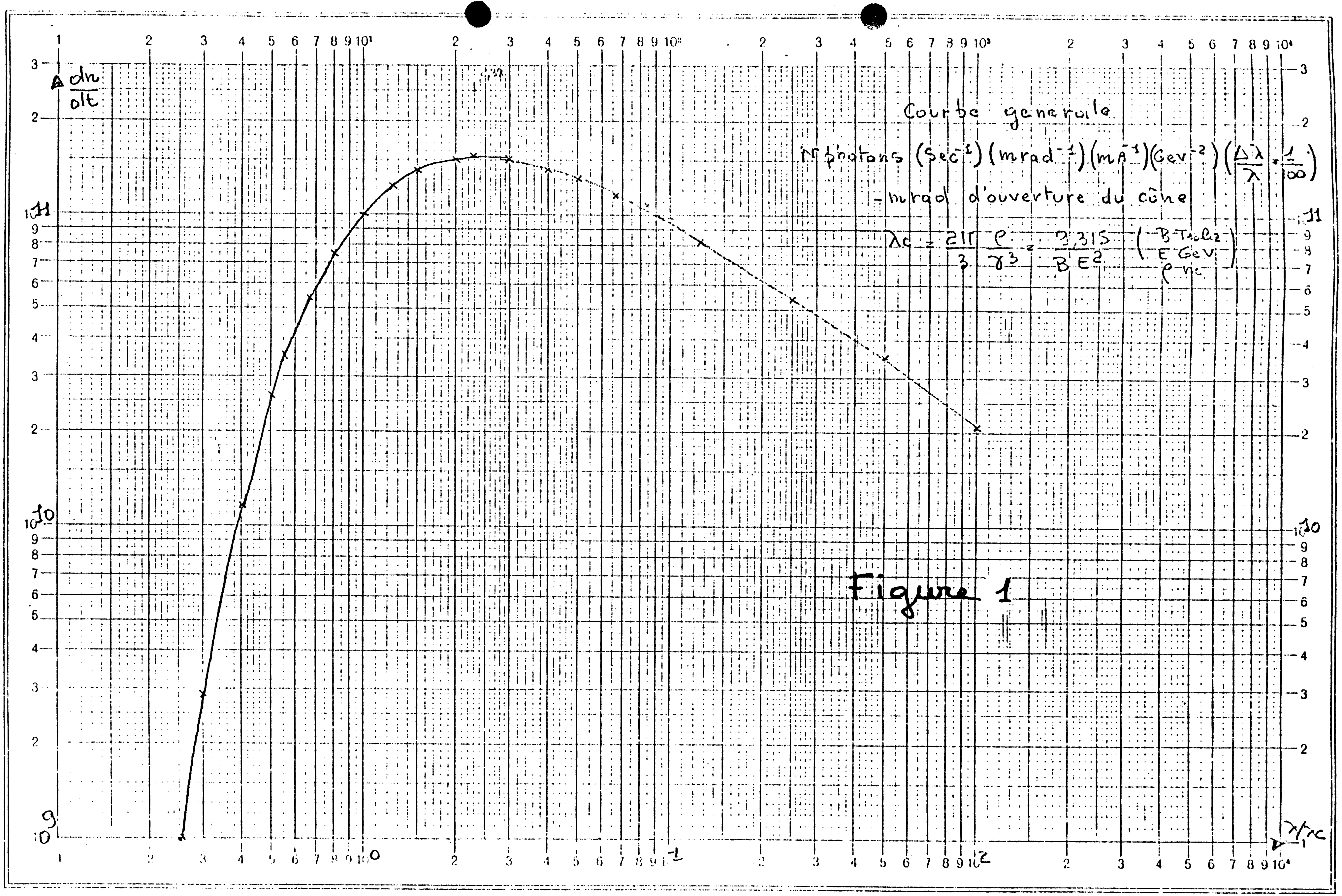
Photon energy	Scattering[a]		Photoelectric K,L and M shells	Pair production		Total[b]	
	With coherent	Without coherent		Nucleus	Electron	With coherent	Without coherent
Mev	Barns/atom	Barns/atom *	Barns/atom	Barns/atom	Barns/atom	cm²/g	cm²/g
0.01	29	8.32	1170			26.8	26.3
.015	19	8.18	343			8.08	7.84
.02	15	8.03	141			3.48	3.33
.03	11.5	7.76	39.0			1.13	1.04
.04	9.8	7.51	15.2			0.558	0.507
.05	8.8	7.29	7.3			.360	.326
.06	8.1	7.10	4.0			.270	.248
.08	7.26	6.72	1.61			.198	.186
.10	6.79	6.41	0.78			.169	.161
.15	5.96	5.77	.21			.138	.134
.20	5.39	5.29	.080			.122	.120
.30	4.64	4.60	.020			.104	.103
.40	4.14	4.12	.010			.0927	.0922
.50	3.78	3.76				.0844	.0840
.60	3.49	3.48				.0779	.0777
.80		3.06					.0683
1.0		2.75					.0614
1.5		2.23		0.0076			.0500
2.0		1.903		.030			.0432
3.0		1.496		.086	0.0002		.0353
4.0		1.247		.140	.0006		.0310
5.0		1.077		.186	.001		.0282
6.0		0.952		.227	.002		.0264
8.0		.778		.295	.005		.0241
10		.663		.353	.008		.0229
15		.490		.460	.014		.0215
20		.393		.539	.019		.0212*
30		.286		.647	.027		.0214
40		.227		.726	.033		.0220
50		.1893		.782	.038		.0225
60		.1630		.828	.042		.0231
80		.1284		.896	.049		.0240
100		.1065		.944	.055		.0247

[a] Data in the first column is given by the sum of coherent scattering and of incoherent scattering from the Klein-Nishina formula corrected for binding effects. In the second column incoherent scattering is given by the Klein-Nishina formula for free electrons.

[b] Barns/atom x 0.02233 = cm²/g

* Energy region in which dipole absorption attains a maximum cross section.

Extrait du livre
X-rays attenuations
coefficients from 10 K
to 100 MeV page 30
B. GRODSTEIN
National Bureau
of Standard
C 582/62. 539.122 N.



Courbe generale

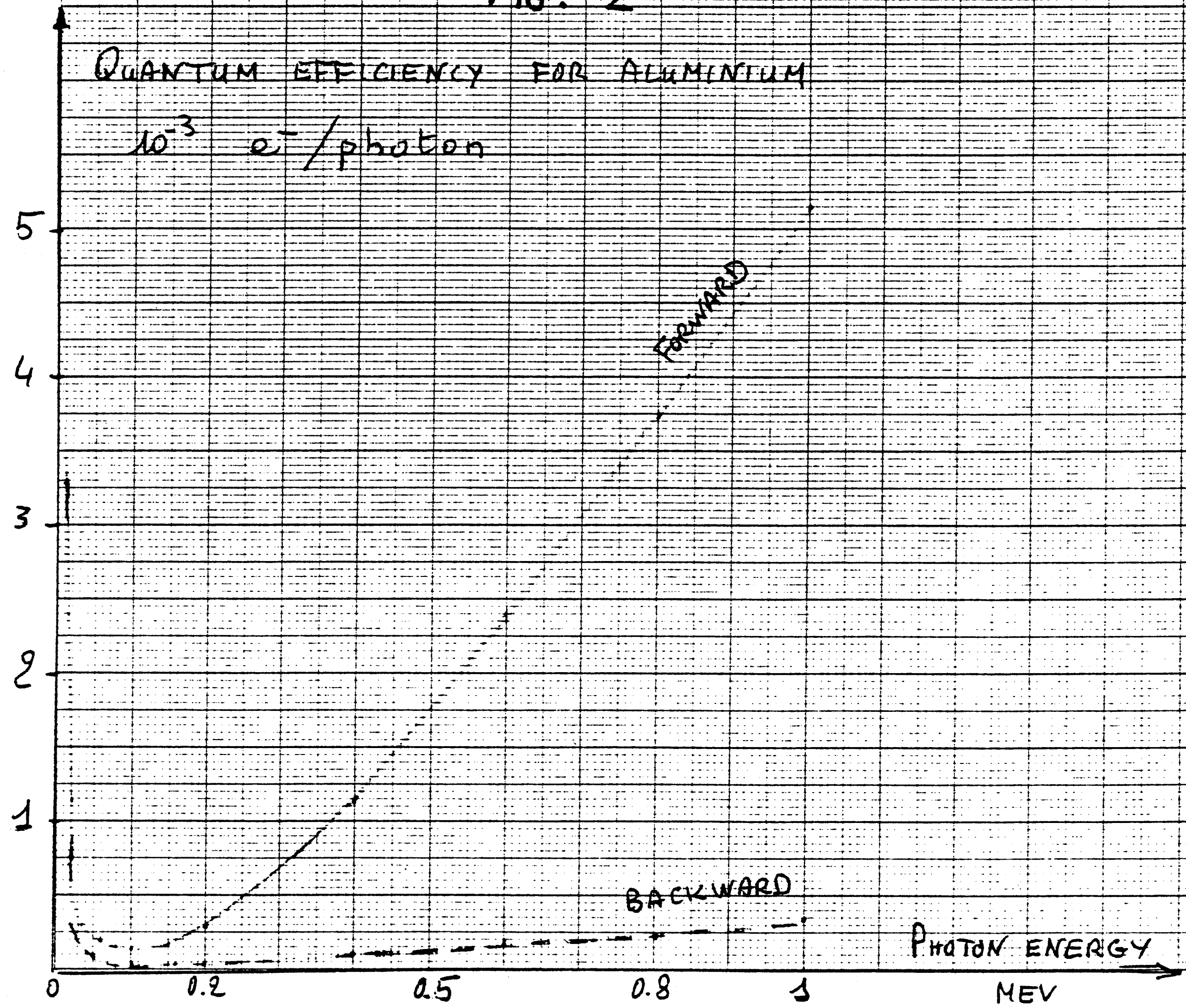
N photons $(sec^{-1})(mrad^{-1})(mA^{-1})(Gev^{-2})\left(\frac{\Delta\lambda}{\lambda} = \frac{1}{100}\right)$

- mrad d'ouverture du cône

$$\lambda_c = \frac{2\pi}{3}\frac{\rho}{\gamma^3} = \frac{3{,}315}{B\,E^2} \begin{pmatrix} B \text{ Tesla} \\ E \text{ GeV} \\ \rho \text{ m} \end{pmatrix}$$

Figure 1

FIG. 2



QUANTUM EFFICIENCY FOR ALUMINIUM

10^{-3} e^-/photon