ABSORBED DOSE AND ENERGY DEPOSITION CALCULATION DUE TO

SYNCHROTRON RADIATION FROM PETRA, HERA AND LEP

by

Chiri Yamaguchi

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ABSTRACT

The Monte Carlo code EGS3 has been used to calculate the
absorbed dose due to synchrotron radiation. The dose to RPL glass
dosimeters located in the air gaps of a dipole magnet and the
radial dose distribution in the PETRA tunnel have been obtained.
The results are compared with the values measured by Dinter and
Tesch. The photon energy spectrum in various regions of the mag-
net gap is given. Similar calculations have been done for HERA
and LEP. The absorbed dose and energy deposition fractions in
various components of the dipole magnet are given as a function of
the thickness of the lead shield. The radial dose distribution in
the LEP tunnel are also presented. Some results for HERA are com-
pared with the calculated values reported by Kötz.

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1. INTRODUCTION

When a charged particle moves on a circular orbit with a
highly relativistic velocity, it emits electromagnetic radiation
generally known as synchrotron radiation. It has a continuous
spectrum which, e.g. in the case of PETRA energy regions, ranges
from infrared to the hard x-ray region of a few hundred keV. It is
highly directional and is emitted along a tangent to the circulating
particle orbit in a narrow cone of the angle $m_o c^2/E$ in the labora-
tory system, where m_o is the rest mass and E is the energy of the
particle.

The photon spectral density is given by Schwinger[1] as follows:

$$\frac{d^2N}{dE \cdot dt} = \frac{5.320 \times 10^{11}}{[E(GeV)]^2} \, G(x) \qquad \text{(photons MeV}^{-1}\text{s}^{-1}) \qquad (1)$$

$$\frac{d^2N}{dE \cdot d\ell} = \frac{17.75}{[E(GeV)]^2} \, G(x) \qquad \text{(photons MeV}^{-1} \text{ m}^{-1}) \qquad (2)$$

where $G(x)$ is the integral of a modified Bessel function $K_{5/3}$, and
it is expressed as:

$$G(x) = \int_x^\infty K_{5/3}(t)\,dt, \quad x = \frac{E}{E_c}.$$

The energy E_c in the above equation is called critical energy
and it is defined as the energy below which half of the total power
is radiated and half above. In equation   it is expressed as:

$$E_c = 2.218 \frac{[E(GeV)]^3}{R(m)} \qquad (3)$$

The radiation power loss ΔE per revolution of an electron in
a circular orbit of radius R is expressed as follows:

$$\Delta E(keV) = \frac{88.46 [E(GeV)]^4}{R(m)} \qquad (4)$$

The synchrotron radiation strikes the water-cooled outer wall of the vacuum chamber at a small grazing angle of 24 mrad in PETRA and 7 mrad in LEP. A great amount of the synchrotron radiation is absorbed at this position resulting an ionization of cooling water. The scattered gamma radiation brings the formation of ozone in the air of the tunnel and radiation damage to various accelerator equipments. Adding a few mm thick lead shielding around the vacuum chamber reduces the absorbed dose in the tunnel to a great extent.

Some measurements of absorbed dose due to the synchrotron radiation in the PETRA tunnel have recently been reported by Dinter and Tesch[2]. The present work deals with the absorbed dose calculation for the measurements using the electromagnetic shower EGS program developed by Ford and Nelson[3]. It also provides some other absorbed dose calculations from the synchrotron radiation for the forthcoming projects HERA (Hamburg) and LEP (Geneva).

2. DOSE CALCULATION

2.1 Concept of dose calculation

The EGS Code system (version 3), referred as EGS3, is a package of computer programs that simulates the development of electromagnetic cascade showers in various media using the Monte Carlo method. It outputs the fraction of energy deposited in various regions of interest. The user is required to prepare his own MAIN user code and a geometry subroutine HOWFAR and an output subroutine AUSGAB.

A new MAIN user code has been prepared[4] to obtain the photon spectrum and to calculate the absorbed dose in the air region from it. When the radiation equilibrium between primary photons and secondary electrons is established, the absorbed dose D(rad) of a material exposed to gamma radiation is given by[5]

$$D = 1.60 \cdot 10^{-8} \Sigma \phi_i E_i \left(\frac{\mu_{en}}{\rho}\right)_i t , \qquad (5)$$

where,

ϕ_i = the flux density in $cm^{-2}s^{-1}$ for the i-th photon in the region of interest (ROI),

E_i = the energy of the i-th photon in MeV,

$(\mu_{en}/\rho)_i$ = mass energy absorption coefficient in $cm^2 g^{-1}$ for the i-th photon in the medium, and it is a function of photon energy,

t = exposed time in s.

The mass energy absorption coefficient μ_{en}/ρ is expressed as follows:

$$\frac{\mu_{en}}{\rho} = \frac{1}{\rho}\left[\iota(1-f) + \sigma\frac{\bar{E}}{h\nu} + \kappa\left(1 - \frac{2mc^2}{h}\right)\right](1-G) , \qquad (6)$$

where

ι = photoelectric cross section,

σ = total Compton cross section,

κ = pair production cross section,

f = fluorescent x-ray fraction,

G = fraction of energy lost by secondary electrons, in bremsstrahlung processes

Thus, in the present calculation whenever the term absorbed dose in the "air" region appears, e.g. the region at a certain distance from the magnet, it represents the absorbed dose in the RPL (radiophotoluminescent) glass dosimeter which shall be located in the region. This is confirmed by the fact that we are generally interested in the absorbed dose in various accelerator equipments and most of which can be well represented by aluminum whose mass energy absorption coefficient is very much similar to that of the glass dosimeter[6].

In eq. 5 the term $\phi_i E_i$ gives energy flux density for the i-th photon with its energy E_i, and the product $\phi_i E_i \left(\frac{\mu_{en}}{\rho}\right)_i t$ is equal to Kerma (kinetic energy released to matter), when fraction of energy lost by secondary electrons in bremsstrahlung processes is negligible (i.e. G = 0). When the radiation equilibrium is not established, the calculated Kerma values overestimate the actual absorbed dose to some extent. In the main user code the average value of mass energy absorption coefficient for RPL glass is used for each of the energy

bins which the user has to specify. The mass energy absorption coefficient for the glass dosimeter has been calculated from the table of ref. 7 based on its elemental composition.

When the photons are coming into a region homogeneously from every direction, the photon flux density can be expressed as the number of photons per unit time that pass through a sphere which has a unit cross-sectional area. In the present calculation, however, the photon flux density ϕ_i in eq. 1 for the region of interest (ROI) which was filled with air was calculated assuming that the photons were coming into the region from one side (x-y plan in Fig. 1). The x, y and z dimensions of each ROI in the calculation for PETRA were 1.6 x 1.6 x 2.0 cm^3. (The dimension in x-direction can actually be any length because the absolute number of photons per any magnet length that hit the vacuum chamber wall can be obtained easily.) This assumption overestimates the photon flux density by a factor of 1.5 when the photons are coming into the ROI homogeneously. (The factor is reduced to 1.3 when the region is a cube.)

The output values of the program which give the fraction of energy deposited in each region and the Kerma for the specified regions are normalized to one electron (or positron) and one m of a magnet length. Thus the final figures that give the absorbed dose to the ROI are obtained by multiplying the Kerma by the synchrotron radiation energy loss per m and the total number of the electrons and positrons.

Some useful parameters concerned with the synchrotron radiation from PETRA, HERA and LEP are listed in Table 1. The necessary data for the calculations have been taken from ref. 8 for HERA and from the Pink Book[9] and a recent note[10] for LEP.

2.2 Geometry in calculation

The measurement positions of the synchrotron radiation in the PETRA dipole magnet gap are given in ref. 2. The corresponding geometry used in the present calculation is shown in Fig. 1. The

figure depicts a cross section of the PETRA dipole magnet on y-z plane. The magnet is assumed to be infinitely long in x-direction, and the simulation of electromagnetic shower transportation is carried out three dimensionally. Each region is filled with the corresponding materials such as iron, aluminum, lead, air or vacuum. The synchrotron radiation hits the inside wall of the vacuum chamber with an incident angle of 24.4 mrad toward x-direction. The figure is not drawn in linear scale. The shielding effect of the distributed ion pump in the vacuum chamber has been taken into account by increasing the effective thickness of the vacuum chamber wall.

The geometries used in the calculation for HERA and LEP are shown in Figs. 2 and 3, respectively. The radial dose distribution in the tunnel was calculated by using the slightly modified geometries given in ref. 4.

2.3 Computer and computing time

Two IBM/370-168 and one IBM/3033 central processing machines are installed at DESY. They are operated by NEWLIB/TSO time sharing system. Each job was run for 16 min IBM/370-168 equivalent CPU time. In order to check a stochastig variation in the results the job with equal geometrical parameters was repeated at least three times by changing the random number generation seed. In the case of PETRA the calculation was repeated 25 times, or 400 min CPU time was provided.

3. RESULTS OF CALCULATION

3.1 PETRA

3.1.1 Absorbed dose in the dipole magnet air gap

The results of the calculation for the measurements by Dinter

and Tesch are compated in Table 2. The figures are expressed in
rad and are normalized to an integrated current of 100 mA h. The
corresponding figures agree with each other within a factor of two,
which is very good in the complicated Monte Carlo calculation.
Since the energy flux density was calculated assuming that the
photons were emerging the brick geometry through one side, as
stated in section 2.1, the calculated values were overestimated
by a factor of 1.5 when the photons were coming into the regions
of interest homogeneously from every direction. The photon dis-
tribution around ROI = C and A showed more or less this tendency,
which explains partly the discrepancy between the calculation and
measurement values for these regions. The standard deviations
of the calculated results which were obtained by 25 runs of the
program with different random generation seeds are also given in
the table. Since the errors of the complicated Monte Carlo calcu-
lation cannot simply be measured by the standard deviation, they
only give a criterion of the error estimation.

Table 3 shows the deposited energy fraction of the synchrotron
radiation power from PETRA in the various accelerator components.
A great amount of the synchrotron radiation power is absorbed in
the vacuum chamber, i.e. 70% at 17 GeV operation and 54% at 21 GeV.
Further, the energy deposition in the vacuum chamber is performed
at the wall and "nose" of the chamber where the synchrotron radia-
tion directly hit the chamber. This amounts 88% in 17 GeV and 92%
at 21 GeV. This can be seen from Fig. 5 in which detailed deposi-
ted energy fractions in the vacuum chamber and the lead shields
in its both sides are shown.

3.1.2 Photon energy fraction spectra

Fig. 4 gives the energy fraction spectra for the regions in
the dipole magnet air gap where the RPL glass rods were located.

Each step of the histogram shows a fraction of energy per energy
bin to the total energy of the synchrotron radiation. The sum of
the height for the individual energy bins of the histogram for the
input spectrum is normalized to unity. The spectrum for ROI = B
is one just outside the vacuum chamber wall which the synchrotron
radiation hits. Although the photons impinge almost parallel to
the wall and its "effective" thickness seems very large, the
higher energy components are still not absorbed. The photons with
lower energies than 30 keV are all absorbed before they come out
of the vacuum chamber. The main contribution to the energy fraction
is from the photons with energies between 60 and 150 keV. The
spectrum for ROI = A shows that after the 3 mm lead shield, the
photons are greatly absorbed. Even photons with higher energies
are absorbed by a factor of 10 to 100. The contribution from the
photons with energies between 60 and 200 keV is reduced by a factor
of 1000. The photons whose energies are lower than 50 keV are not
observed.

The spectrum for ROI = C which is the region inside the beam
orbit has a similar shape to that for ROI = B, the outside region,
but the former is degraded by a factor of 100 (in higher energy
region) to a few hundreds (in lower energy region). The highest
contribution to the energy fraction is from the 100 to 150 keV
energy bin. This spectrum, afterpassing through the 3 mm lead
shield, changes its shape to: ROI = D. The latter spectrum consists
of photons whose energies are larger than 60 keV, but the energies
of the most photons are between 150 and 300 keV. Thus, the photons
outside the lead shield are hard x-rays.

3.1.3 Radial absorbed dose distribution

The special absorbed dose distribution at beam height in the radial
direction in the PETRA tunnel was also calculated. The geometry
used in the calculation is shown elsewhere[4]. The individual air
regions for which the dose was calculated had y x z dimensions of
10 x 10 cm^2. Fig. 6 shows the results both with and without adding
a 3 mm thick lead shield on both sides of the vacuum chamber in the

PETRA dipole magnet. The vertical lines indicate the variation of the values in several computer runs, and the points are their arithmetic mean values. The distance, r, is measured from the surface of the vacuum chamber.

In both cases the calculated points are well fitted by a function expressed as $(1/r)^{0.8}$. The above results were compared with the measured values of ref. 2. Since the shielding with lead plates of some accelerator parts, i.e. vacuum flanges, bellows etc., is not complete, we cannot take the values calculated for the completely shielded case. The contribution of the radiation escaping through the incompletely shielded parts must be taken into account. The more complete the shielding, the more prominent its contribution. The comparison between measurement and calculation is shown in Fig. 7. The solid line was drawn by the eye. The calculated data corresponds to the situation that 3% of the total accelerator ducts is not shielded, which might be a reasonable assumption. On this assumption the agreement between calculation and measurement is very good.

3.2 HERA

The absorbed energy fractions for various accelerator components of the HERA dipole magnet are shown in Fig. 8 as a function of the thickness of the lead shield. The geometry used in the calculation is shown in Fig. 2. The thickness of the lead shield was assumed to be the same on both radial sides of the vacuum chamber. No lead shield was mounted on the above and the bottom of the chamber. The vacuum chamber was assumed to be made of copper, as suggested in ref. 8, and had wall thickness of 4 mm.

Because of a good shielding effect of the copper vacuum chamber, it absorbs 93% of the synchrotron radiation energy. Since the lead shield is outside the chamber, the value is inde-

pendent of the lead thickness. The fraction of energy absorbed by the magnet yoke hardly changes as a function of the lead thickness. It is 5.2% at zero lead thickness and 4.3% above 2 mm. This is explained by the fact that most of the synchrotron radiation energy is absorbed in the vacuum chamber and that the absorbed energy fraction for the lead shield inside the yoke increases only slightly as a function of lead thickness, i.e. from 1.1% at 2 mm to 1.2% at 5 mm. This fact also indicates that even though the lead shields are added to the top and the bottom of the vacuum chamber, the absorbed energy fraction in the yoke would not be reduced much in the present case.

The fraction of nergy leaving the magnet gap and one absorbed in the excitation coil decrease drastically as the lead thickness increases. At 5 mm lead thickness the fraction of energy is decreased by a factor of 50 less than that at 0 mm, and the latter by a factor of 30. Without lead shield the absorbed dose to the coil reaches 2.6×10^9 rads on average for 25,000 h operation with a beam current of 56 mA, but is reduced to 1×10^8 rads with 5 mm lead shield.

Absorbed dose to the coil insulation and to a component at the entrance of the magnet is plotted in Fig. 9 as a function of lead thickness. The former was calculated for two regions of interest (ROI), one of which was the region in front of the coil (ROI = 84) and the other behind (ROI = 106) (see Fig. 2). The values are normalized to an integrated current of 1.4×10^3 A h, which was obtained assuming a running time of 25,000 hours with a beam current of 56 mA as stated above.

When the chamber is not shielded, the maximum absorbed dose to the coil insulator reaches 1×10^{10} rads for 25,000 hours operation. This is, however, reduced to 3×10^8 rads, or by a factor of 30, when 5 mm thick lead shield is mounted on the radial side of the chamber. This amount of dose would not cause a serious radiation damage to the insulator. The ratio of absorbed doses to the insulator in front of and behind the coil is about 10, and it

is almost independent on the lead thickness.

The absorbed dose to a component at the opening of the magnet gap sums up to 1.5×10^{10} rad during the same period. The dose is strongly dependent on the lead thickness, and it could be reduced to 2×10^{8} rads with 5 mm thick lead. The absorbed dose to a component at the beam height and 1 m from the magnet gap is also plotted in Fig. 9.

Kötz[11] has recently simulated the same problem for HERA project with his Monte Carlo code in which only photoelectric and Compton scattering effects were taken into account. The code, however, included the polarization of the synchrotron radiation which the EGS code has not. Some of the present results are compared with his results in Table 4. They agree well with each other within a factor of 4, mostly 2. Larger discrepancies are thought to be caused by the differences in the geometry in both calculations and essential factors in both codes.

3.3 LEP

3.3.1 Absorbed dose in various components

The LEP dipole magnet geometry used in the calculation is given in Fig. 3. The dimensions are not drawn in linear scale. The thickness of the ceramic insulation walls were fixed in the calculation. The lead thickness on the top and the bottom of the chamber was fixed at 3 mm whenever lead shield was added to the chamber. For zero lead thickness all the lead regions were filled with air.

The absorbed doses per integrated beam current of one Ah to a component at both radial regions (ROI - 9 and 174) of the vacuum chamber are plotted in Fig. 10 as a function of the thickness of the lead shield. The data in Table 1 show that the integrated current for ten years will be 276 Ah at 51.5 GeV operation assuming a 5000 hours run per year with a design beam current of 5.52 mA

per beam. Thus, the absorbed dose of 10^{8} rads/Ah corresponds to the cumulated dose after ten years of $(10^{8}$ rads/Ah) x (276 Ah) = 2.8×10^{10} rads. The absorbed dose for any other periods can be obtained similarly.

Table 5 gives some of the absorbed dose values obtained from Fig. 10 for the regions in the air gap of the magnet. The region ROI = 9 is inside the beam orbit and the region ROI = 174 is outside. The dose reduction factor is the inverse of the ratio of the absorbed dose with lead shield to that without. The dose reduction factors for this region are less than those for the region 9 in spite of the thicker lead shield thickness. The reason for this feature can be easily understood if one considers the difference in the photon energy spectrum in both regions. See, for example, the photon energy spectra for the corresponding regions in the case of PETRA (ROI=D and A in Fig. 4). The spectrum in the region outside the beam orbit contains both higher and lower energy photons than that in the inside region. The photons in the inside region have been more multi-scattered from the point where the synchrotron radiation hits the vacuum chamber wall than those in the outside region. This is caused by the larger distance to the inside region from the impinging point and also by the geometry of the vacuum chamber.

The absorbed energy fractions to the vacuum chamber, excitation coil and ceramic insulator (only to the wall outside the beam orbit) and the energy fraction leaving the magnet gap are plotted as a function of the lead thickness in Figs. 11, 12 and 13 for operation energy of 51.5, 85 and 125 GeV, respectively. In any case the absorbed energy fraction to the vacuum chamber is independent of the lead thickness, as mentioned in section 3.1. The values are 0.58, 0.50 and 0.57 for 51.5, 85 and 125 GeV operations, respectively. The errors accompanied to them are far smaller than the differences among themselves. The absorbed energy fractions are not a simple linear function of nergy, since the total energy impinging the vacuum chamber is normalized to unity in every case.

The error bars show the variation of the data in several runs of the program with different radom number generation seeds, as stated in previous section.

Without shield the absorbed doses to the coil after a running time of ten years, or 50,000 hours, reach 1.0×10^9 rads (52.5 GeV), 1.9×10^{10} rads (85 GeV) and 5.8×10^{10} rads (125 GeV). With these values and the graphs in Fig. 11 ~ 13 one can easily find the absorbed dose to the coil when a certain amount of the lead shield is added to the chamber.

At 51.5 GeV operation a 6 mm thick lead shield can reduce the absorbed energy fraction for the coil by a factor of 60 and the energy fraction leaving the magnet gap by 600. At 85 GeV the same thickness of lead can reduce the former by a factor of only 7 and the latter by 9. At 125 GeV operation it requires the lead thickness of 19 mm to reduce the absorbed dose fraction to the coil by a factor of 10, and 17 mm to reduce the energy fraction leaving the magnet gap by the same factor.

Since the magnet gap width is restricted, the thickness of the lead shield at the top and the bottom of the vacuum chamber is also limited. However, the thickness of 3 mm which was used in the present calculation might be enough if we take into account the results in the calculation for HERA (see section 3.2). The absorbed energy fraction for the ceramic insulator was given only for the wall outside the beam orbit where the absorbed dose is actually the highest among the other regions of the insulator.

3.3.2 Radial absorbed distribution

The radial absorbed dose at the beam height in the LEP tunnel was calculated using the same geometry[4], but of course not the same dimensions, as for PETRA. The results are shown in Figs. 14,

15 and 16 for the operation at 51.5, 85 and 125 GeV.

When no lead shield is provided to the vacuum chamber, the radial absorbed dose distribution decreases according to the inverse distance law in the case of 51.5 and 85 GeV operations. At 125 GeV operation it is well fitted by the inverse distance function (solid line) in the smaller distance regions (r < 60 cm), but in larger distance regions it is better fitted by a function expressed by $(1/r)^{0.8}$.

Some of the reasons for above features are given as follows: Firstly, when the lead shield is added to the chamber, the dimensions of the "effective" radiation source becomes broader in the vertical direction because of its shielding effect and multiple scattering of the synchrotron radiation in the magnet yoke. Secondly, the shielding makes the outcoming spectrum harder, as shown in the previous section. This makes the radial absorbed dose distribution curve more flat.

Höfert[12] has recently calculated the absorbed dose to a glass dosimeter at 1 m from the LEP machine. The results were 5.4×10^3 rads/Ah at 51.5 GeV operation and 9.3×10^5 rads/Ah at 85 GeV for the vacuum chamber shielded with 8 mm thick (outer side of the beam orbit) and 3 mm thick (inner side, bottom and top of the chamber) lead.[*] The corresponding values in the present calculation are, from Figs.14 and 15, 1.2×10^4 rads/Ah and 1.0×10^6 rads/Ah at 51.5 GeV and 85 GeV operations, respectively. Both data agree well with each other.

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[*] The original data are given for an operation of 5,000 hours with the beam current listed in Table 1 in the present paper.

4. CONCLUSION

Based on the above results of the calculation the following remarks are given as conclusion.

4.1 PETRA

i)   The calculated values by EGS3 of the absorbed dose to the glass dosimeter located in four regions inside and outside the dipole magnet gap agree within a factor of two with the corresponding values given from the measurement by Dinter and Tesch.

ii)   The calculated absorbed dose distribution in the radial direction at the beam height is expressed by $(1/r)^{0.8}$, where r is a distance from the surface of the vacuum chamber wall. It agrees with the experimental data well providing that there is 3% in length of the incomplete shielding sections along the storage ring.

iii) The vacuum chamber absorbs 70% of the synchrotron radiation energy at 17 GeV operation and 54% at 21 GeV operation. Further, the energy deposition in the chamber is concentrated at the wall which the synchrotron radiation hits.

4.2 HERA

i)   As much as 93% of the synchrotron radiation energy is absorbed by the 4 mm thick copper vacuum chamber. Because of this high absorbed energy fraction no lead shield would be required at the top and the bottom of the vacuum chamber.

ii)   When the chamber is not shielded, the cumulated absorbed dose to the coil insulation dureing 25,000 hours operation

reaches 1×10^9 rads. This is reduced to 3×10^7 rads with adding a 5 mm thick lead to the radial side of the chamber.

iii) The absorbed dose to the coil during the same period reaches 3×10^9 rads without shield and 1×10^8 rads with 5 mm thick lead shield.

iv)   The absorbed dose to a component at the opening of the dipole magnet gap sums up to 1.5×10^{10} rads for 25,000 hours operation. Lead shield of 5 mm in thickness can reduce this value to 2×10^8 rads.

v)   The present results agree well with the calculated values by Kötz.

4.3 LEP

i)   The absorbed energy fractions of the synchrotron radiation energy for the aluminum vacuum chamber are 0.58, 0.50 and 0.57 for 51.5, 85 and 125 GeV operation, respectively.

ii)   Without shielding the vacuum chamber the absorbed dose to the coil during ten years (a running time of 50,000 hours) reaches on average 1.0×10^9 rads (51.5 GeV), 1.9×10^{10} rads (85 GeV) and 5.8×10^{10} rads (125 GeV).

iii) At 51.5 GeV operation 6 mm lead shield can reduce the absorbed energy to the coil and the energy fraction leaving the magnet by a factor of 60 and 600, respectively. At 85 MeV, however, the same thickness can reduce them by a factor less than 10, giving the absorbed dose of 7×10^9 rads to the coil during 10 years.

iv)   At 125 GeV even a 19 mm thick lead shield can reduce the

absorbed dose to the coil by a factor of only 10. Some other measures, such as filling the outside chamber region in the magnet gap by concrete, will have to be taken.

v) Without shield the absorbed doses to a component at the opening of the dipole magnet during ten years arrives at the level of 4.4×10^9 rads (52.5 GeV), 2.7×10^{10} rads (85 GeV) and 4.9×10^{10} rads (125 GeV). Those with lead shield can be obtained from the given figure in the text.

vi) When no lead shield is provided to the vacuum chamber, the radial absorbed dose distribution decreases according to $(1/r)$ or $(1/r)^{0.8}$. When the lead shield is added, the radial absorbed dose decreases less abruptly in the regions close to the vacuum chamber wall ($r \sim 30 \sim 40$ cm).

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Table 1   Some useful parameters concerned with the synchrotron
            radiation from PETRA, HERA and LEP

	PETRA	HERA	LEP		
			Stage I		Stage II
Energy (GeV)	19	30	51.5	85.0	125
Bending radius (m)	192	550	3104	3104	3104
Critical energy (keV)	79.2	109	97.6	439	1396
Circulating current per beam (mA)	10	56	5.52	9.25	6.16
Synchrotron radiation loss/turn (MeV/turn)	60.0	130	200	1490	6960
Synchrotron radiation loss/m (keV/m)	52.1	37.6	10.3	76.4	357
Integrated current in 10 years[*] (Ah)	560	2800	276	463	308

[*]Annual operation of 5000 hours

Table 2 — Comparison of measured and calculated absorbed doses for the RPL glass dosimeters which were located at four positions (A-D) in the PETRA dipole magnet air gap (see ref. 2). The values are expressed in rads per integrated current of 100 mAh.

Energy		Measurement point/Region of interest (ROI)			
		A/114	B/96	C/24	D/6
17 GeV	Measurement	$8.4\pm0.3\times10^3$	$4.8\pm1.2\times10^7$	$1.5\pm0.4\times10^6$	$6.6\pm0.9\times10^3$
	EGS3	$1.6\pm1.3\times10^4$	$2.0\pm0.3\times10^7$	$2.9\pm0.8\times10^6$	$2.9\pm2.5\times10^3$
21 GeV	Measurement	-	-	$1.8\pm0.3\times10^7$	-
	EGS3	$2.6\pm0.7\times10^5$	$4.9\pm0.4\times10^7$		$1.8\pm1.6\times10^4$

Table 3 — Deposited energy fraction calculated by EGS3 of the synchrotron radiation from PETRA in various accelerator components, and absorbed dose (rad/100mAh) at 1m from the surface of the vacuum chamber

Component	Energy 17 GeV	21 GeV
Vacuum Chamber	0.70	0.54
Magnet Yoke	0.22	0.34
3mm Pb shield (inside yoke)	0.071	0.12
" (outside ")	0.002	0.001
Coil (inside yoke)	0.002	0.006
" (outside yoke)	$\sim1\times10^{-4}$	$\sim2\times10^{-4}$
Escaping the magnet	$\sim2\times10^{-5}$	$\sim3\times10^{-4}$
Dose at 1m: with 3mm Pb	6×10^2	5×10^3
without Pb	1×10^5	5×10^5

Table 4 — Energy fraction of synchrotron radiation loss deposited in various components of the HERA dipole magnet and doses to them. Doses are normalised to an integrated current of 1.4×10^3 A h.

	Without lead		with 5 mm thick lead	
	EGS3	Kötz	EGS3	Kötz
Energy fraction				
Vacuum chamber (Cu)	0.932	0.92	0.932	0.92
Lead shield	-	-	0.025	0.055
Yoke	0.05	0.066	0.04	0.02
Coil (Al)	0.004	0.01	$1.4\cdot10^4$	$3\cdot10^{-4}$
Coil insulation	$1\cdot10^{-4}$	$4\cdot10^{-4}$	$1\cdot10^{-5}$	$1\cdot10^{-5}$
Leaving magnet gap	$1.4\cdot10^{-2}$	$6\cdot10^{-3}$	$3\cdot10^{-4}$	$2\cdot10^{-4}$
Doses (rads) to Coil insulation	$1.0\cdot10^{10}$	$3\cdot10^{10}$	$3.0\cdot10^8$	$8\cdot10^8$
Components at magnet opening	$1.6\cdot10^{10}$	$1\cdot10^{10}$	$3.0\cdot10^8$	$3\cdot10^8$

Table 5   Some of the absorbed dose values and the dose reduction factors
for the regions in the air gap of the magnet

	ROI = 9 (Inside the beam orbit)			ROI = 117 (Outside the beam orbit)		
Energy (GeV)	51.5	85	125	51.5	85	125
Absorbed dose (rad/Ah)						
Without lead	1.7×10^7	6.0×10^7	1.5×10^8	5.0×10^7	2.2×10^8	5.5×10^8
With 8 mm lead	4.0×10^4	2.2×10^6	2.3×10^7	–	–	–
With 10 mm lead	–	–	–	3.2×10^4	8×10^6	1×10^8
Dose reduction factor	400	30	7	150	25	5

FIGURE CAPTIONS

Fig. 1   Geometry used in the calculation of the absorbed dose and
deposited energy fraction for PETRA.

Fig. 2   Geometry used in the calculation of the absorbed dose and
deposited energy fraction for HERA.

Fig. 3   Geometry used in the calculation of the absorbed dose and
deposited energy fraction for LEP.

Fig. 4   Photon spectra in various regions of interest (ROI) in
the air gap of the PETRA dipole magnet at 17 GeV operation.

Fig. 5   Deposited energy fraction in various parts of the PETRA
vacuum chamber at 17 GeV operation.

Fig. 6   Radial absorbed dose distribution in the PETRA tunnel (17 GeV).

Fig. 7   Comparison of calculated and measured radial dose distri-
bution in the PETRA tunnel. The solid line was drawn
by eye.

Fig. 8   Absorbed energy fractions in various magnet components
of HERA at 30 GeV operation.

Fig. 9   Absorbed dose to a component at the entrance of the HERA
magnet gap, at 1 m from the magnet gap, and absorbed dose
to the coil insulation. Operation energy is 30 GeV.

Fig. 10   Absorbed dose to a component at both sides of the LEP
vacuum chamber as a function of the lead shield thickness.
The region ROI = 9 is inside the beam orbit and ROI = 174
is outside.

Fig. 11   Absorbed energy fraction for the various components of the
LEP dipole magnet as a function of the lead shield thick-
ness. The operation energy is 51.5 GeV.

Fig. 12   Absorbed energy fraction for the various components of the
LEP dipole magnet as a function of the lead thickness.
The operation energy is 85 GeV.

Fig. 13 Absorbed energy fraction for the various components of the LEP dipole magnet as a function of the lead thickness. The operation energy is 125 GeV.

Fig. 14 Radial absorbed dose distribution as a function of a distance from the surface of the vacuum chamber of LEP.

Fig. 15 Radial absorbed dose distribution as a function of a distance from the surface of the vacuum chamber of LEP.

Fig. 16 Radial absorbed dose distribution as a function of a distance from the surface of the vacuum chamber of LEP.

PETRA

Iron yoke

Aluminum coil or chamber
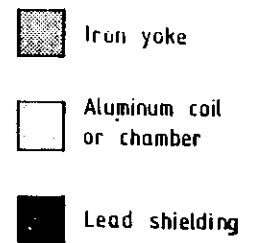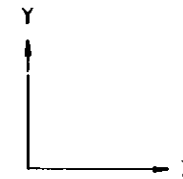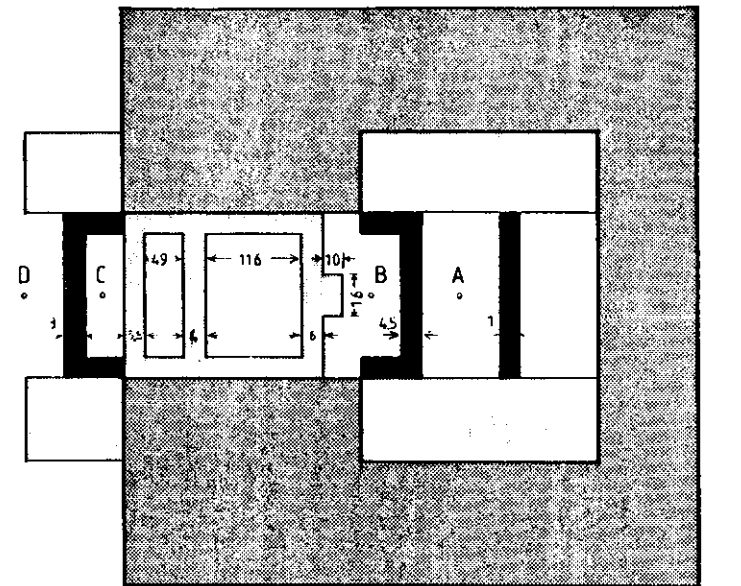
Lead shielding

Scale in mm

FIG 1   33119

HERA
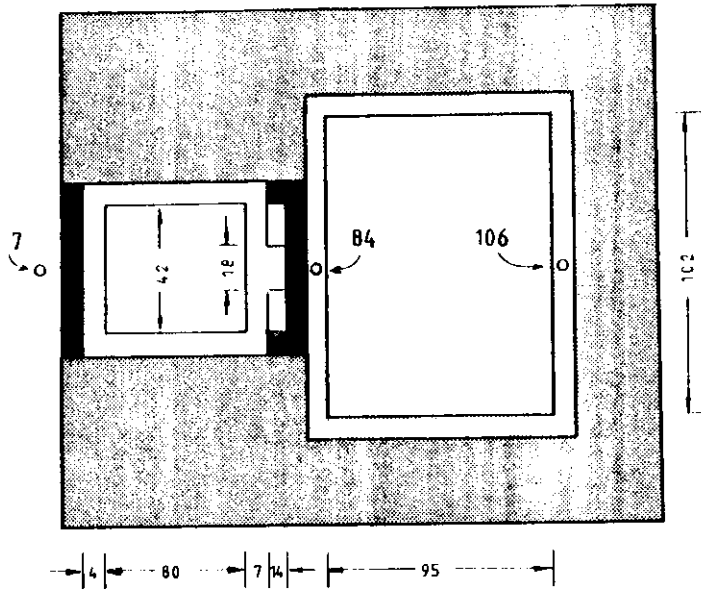
Iron yoke	
Vacuum chamber or coil	
Insulator	
Lead shield	
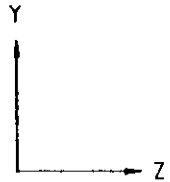
Units: mm

33121

FIG 2

LEP
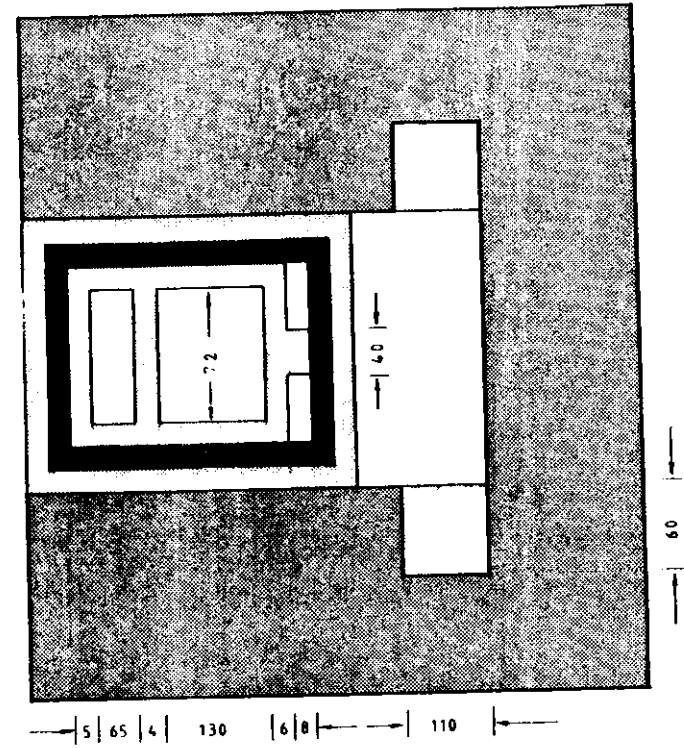
Iron yoke	
Ceramics heat insulation	
Lead shield	
Aluminum coil or chamber	

Units: mm

FIG 3

33120
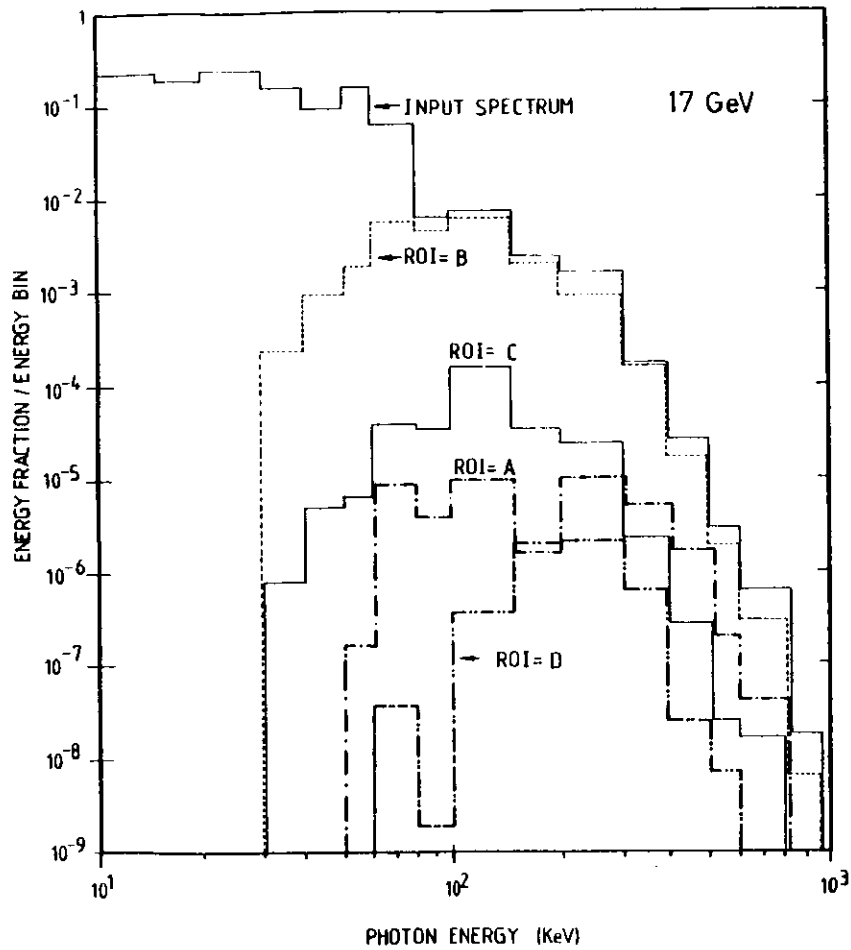
FIG 4
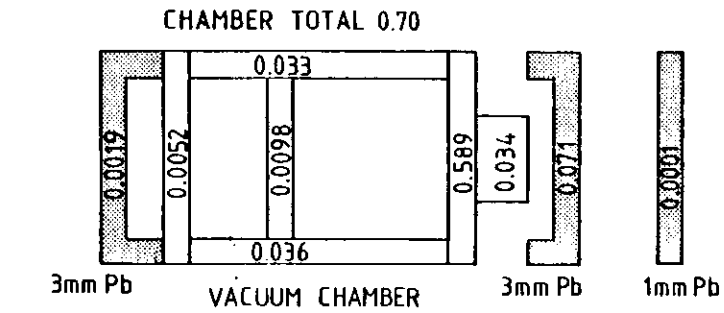
a) DEPOSITED ENERGY FRACTION AT 17 GeV (PETRA)
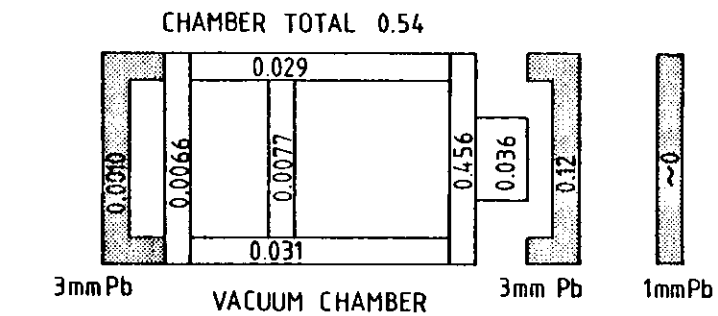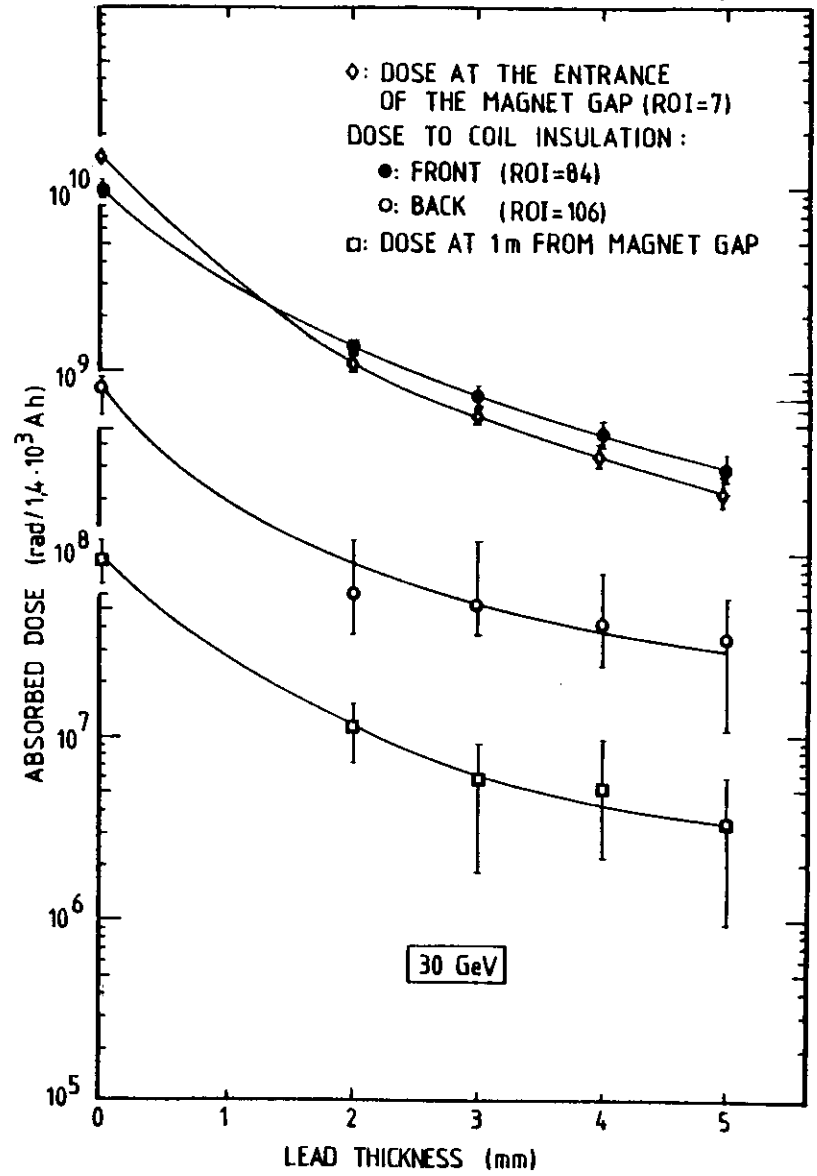

b) DEPOSITED ENERGY FRACTION AT 21 GeV (PETRA)

FIG 5

PETRA 6

17 GeV

SOLID LINE: $1/r^{0.8}$

DOTTED LINE: $1/r$

(I) WITHOUT SHIELD

RIGHT SCALE ⟶

(II) WITH
3mm Pb SHIELD
⟵ LEFT SCALE

ABSORBED DOSE (rad/100 mA h)

DISTANCE FROM THE VACUUM CHAMBER
SURFACE (cm)

FIG 6

● ≙ EXP. DATA (ref. 2)

× ≙ EGS CALCULATION

17 GeV

ABSORBED DOSE (rads / 100 mA h)

RADIAL DISTANCE FROM BEAM POSITION (cm)
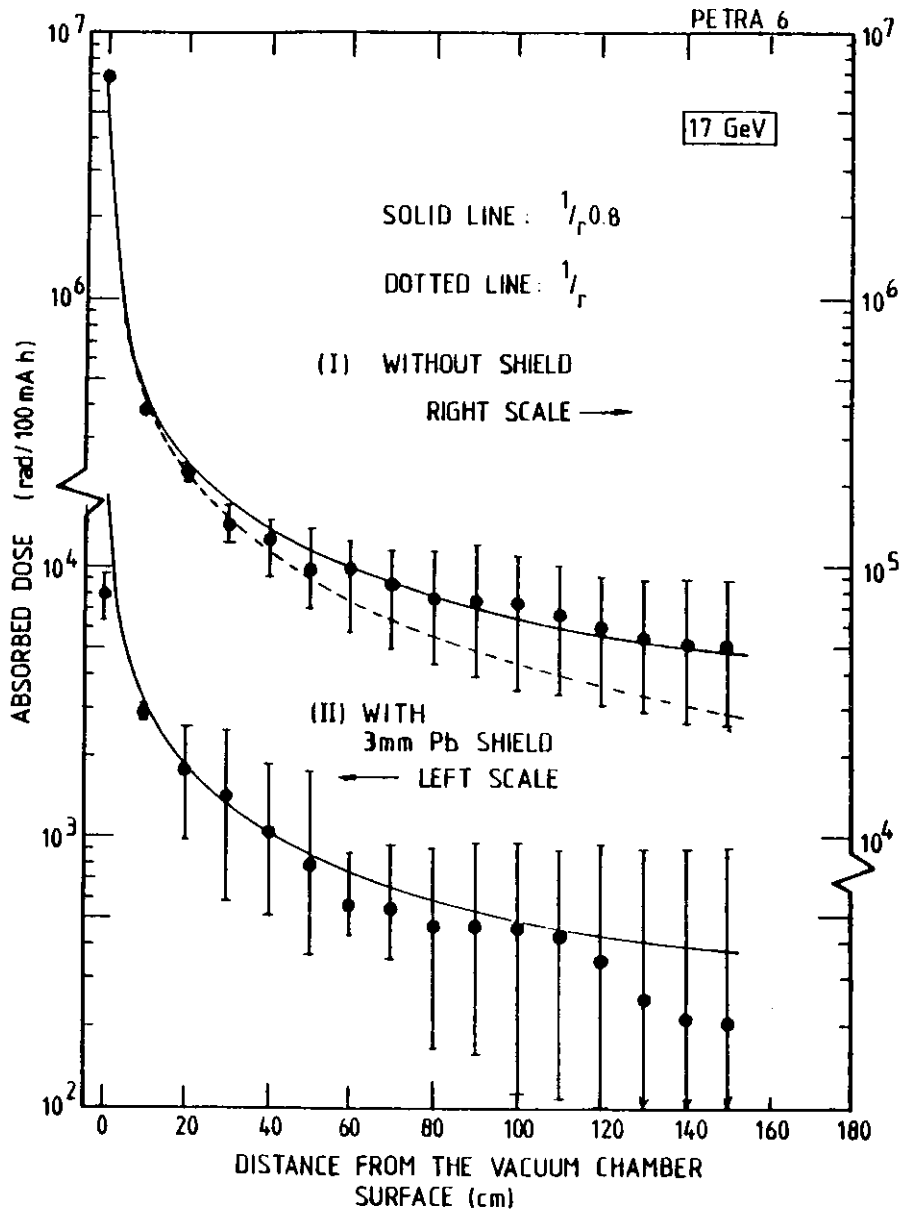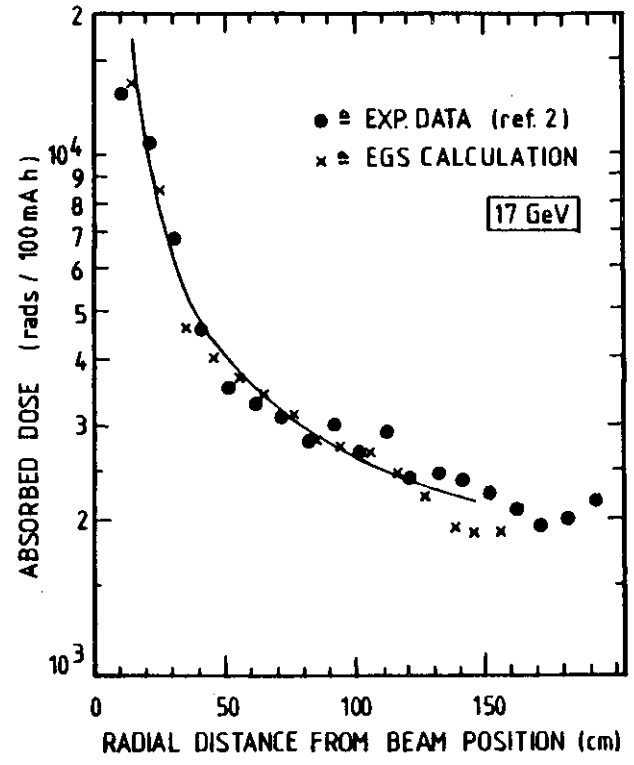
FIG 7
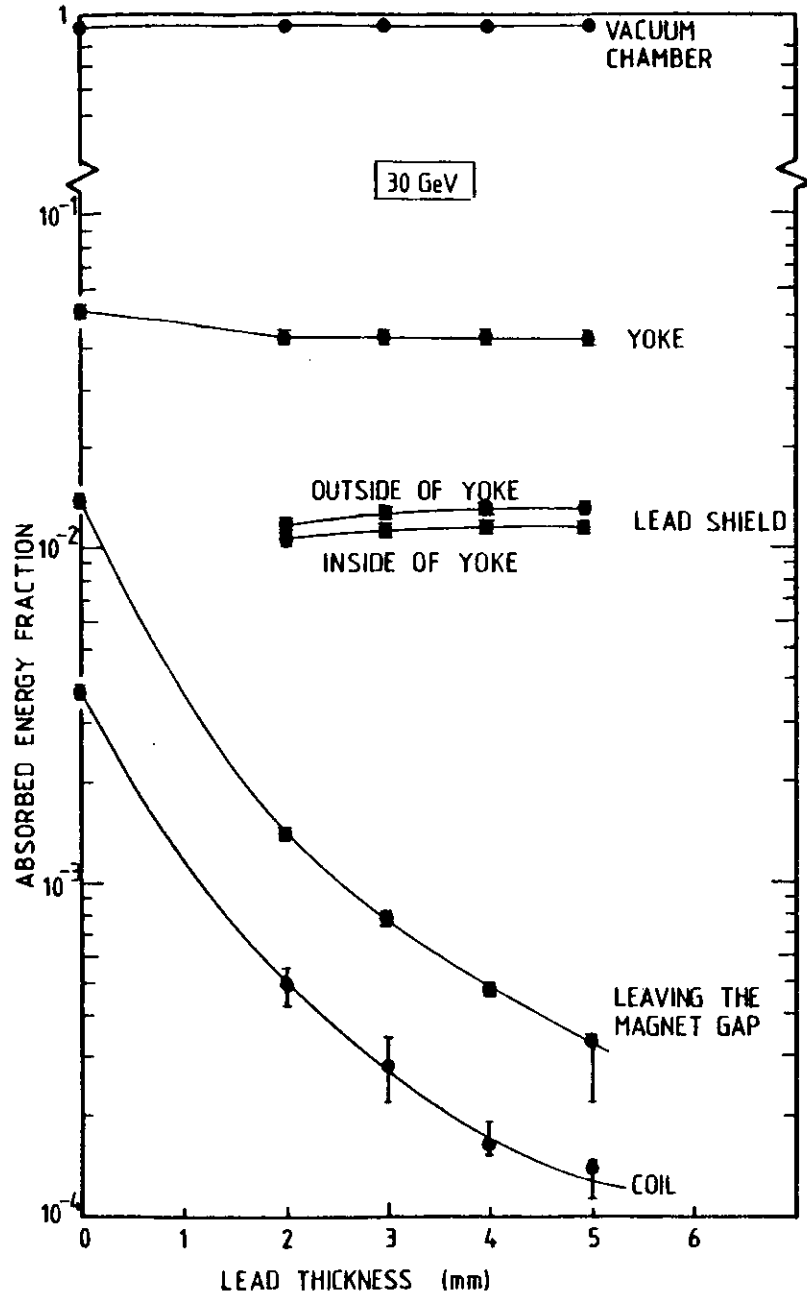
FIG 8

FIG 9
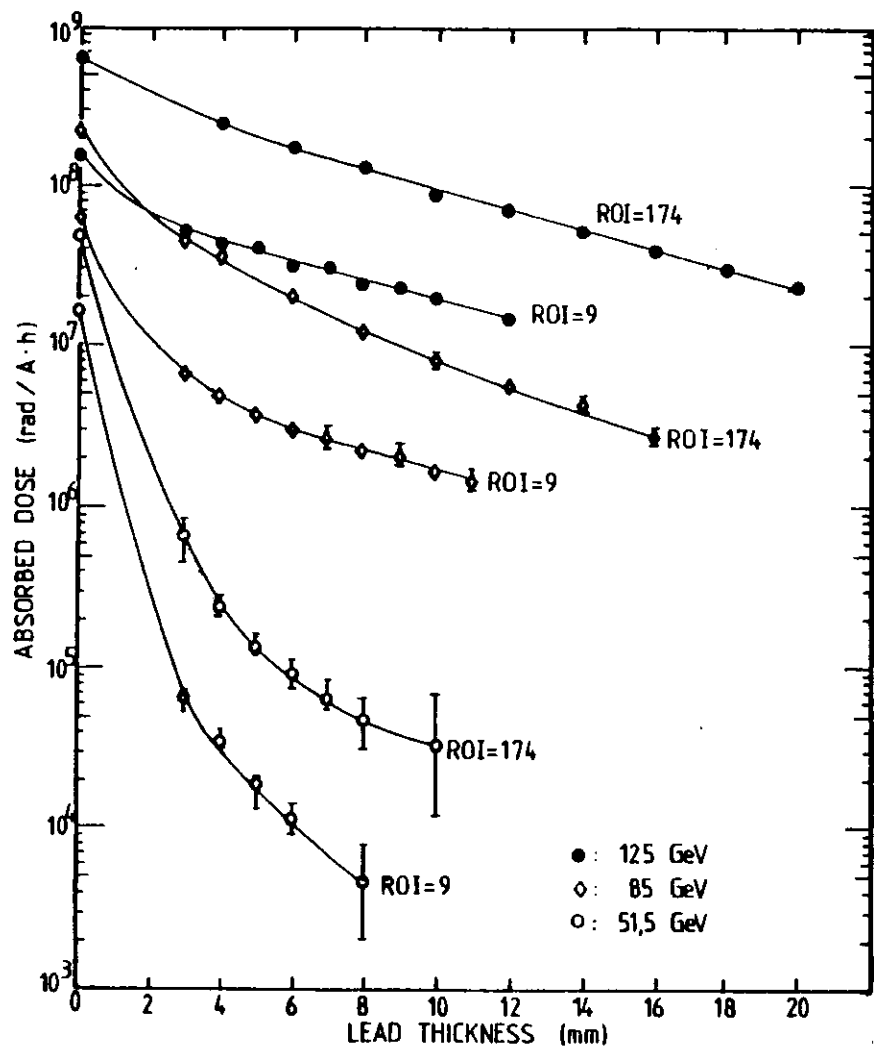
FIG 10
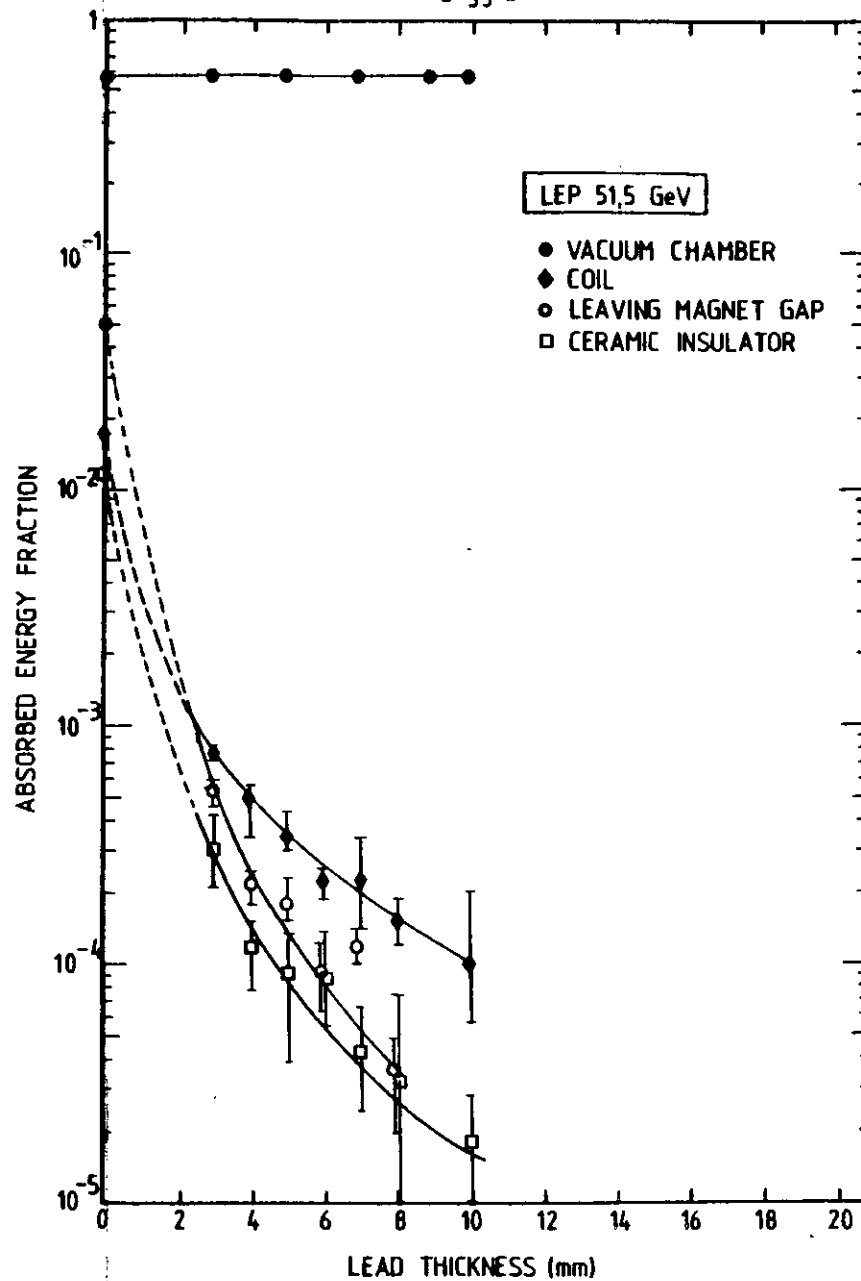
FIG 11
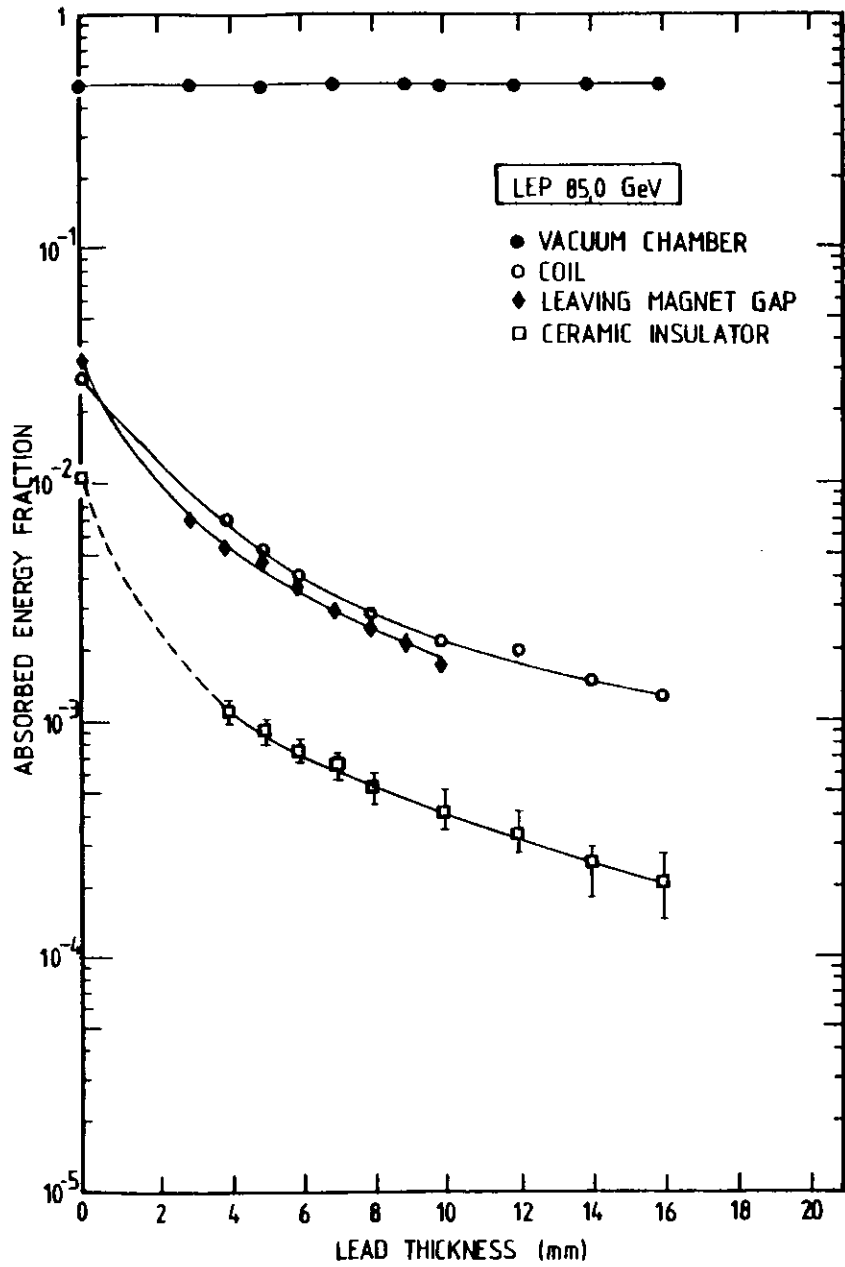
FIG 12

FIG 13

FIG 14

FIG 15

FIG 16