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THE RADIATION PROTECTION SYSTEM FOR LEP

CERN RP Group[*]

ABSTRACT

This note has been prepared as a contribution to the comprehensive LEP Design Report, which will contain a description of the CERN Large Electron–Positron storage ring (LEP) now under construction, adjacent to the existing CERN facilities in France (Pays de Gex) and in Switzerland (Canton de Genève). The present report assesses the radiological implications of the project, and describes all the steps that are being taken to eliminate possible adverse radiation effects. The salient parameters, provisions, and measures that will be used to protect those working on the LEP project, as well as those living in its neighbourhood, are described. It is shown that this system will adequately protect all persons involved, and that the legal requirements of the host countries, the recommendations of the ICRP, and the requirements of the internal CERN rules will be satisfied. This note contains a synthesis of the work of many individuals who addressed themselves to LEP radiation problems within the framework of the LEP Radiation Working Group. A more comprehensive report of the LEP Radiation Protection System is in preparation, and the reader is referred to this document for further information and for due account of the authorship of the different contributions.

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INTRODUCTION

This note describes the radiation protection system for the LEP project, i.e. the pre-injector system, the two injectors PS and SPS, and the main LEP ring. It gives an account of the radiation problems[1] expected and the provisions made for them in the design of LEP, and explains the choice of parameters where these were influenced by radiation protection considerations. The system is designed to minimize any radiation risk for those working with LEP or living in its vicinity, and to protect the installations from radiation damage and radiation-induced malfunctioning. Standards for the protection of the environment and the workers are based on the CERN radiation protection policy[2]. In the assessment of possible risks, due account is taken of the maximum possible performance and utilization of the LEP installations; in the calculations and estimates, reasonable safety factors are applied in choosing conservative physical parameters for the production of radiation, radioactivity, or noxious chemical compounds, and for the attenuation of radiation or the decay and decomposition of radioactive and noxious products, respectively.

On the other hand, for assessing the physical or chemical effects from radiation on components and radiation-sensitive materials, reasonable average parameters are chosen for the LEP beam intensities, duration of operation, and maximum energies.

RADIOLOGICAL REQUIREMENTS

Members of the general public

Consistent with the International Commission on Radiological Protection (ICRP) recommendations, France and Switzerland have independently defined 5 mSv (0.5 rem) as the yearly dose-equivalent limit for any member of the general public. CERN has therefore adopted this limit also for any person on the CERN premises (whether a member of the general public or member of CERN personnel) who is not individually monitored. For those members of the public living outside the fenced CERN site, the radiation protection policy of the Organization aims at a further limitation of their exposure to direct radiation. In addition, the release of airborne radioactivity will be controlled such that it is most unlikely that anyone living near CERN will receive more than 0.2 mSv/y (20 mrem/y) from gaseous releases. Stray radiation and all types of releases will be controlled such that the exposures, by all pathways, of individuals living outside the fence shall not exceed 0.5 mSv/y (50 mrem/y). Table 1 contains a summary of applicable dose limits.

Areas outside the fences will have additional protection, beyond the formal limits just outlined; for the release of prompt radiation and radioactive and noxious products to the environment, ICRP ALARA principles[*] will be applied.

Table 1

Annual dose-equivalent limits (in mSv/y)
Note: To convert from SI units to special radiation units: 1 mSv = 100 mrem.

Population group affected	Recommended by ICRP	As required by France	As required by Switzerland	CERN reference level
Site boundary	5 mSv/y	5 mSv/y	5 mSv/y	Direct radiation at site boundary: 1.5 mSv/y
Individual members of the public outside CERN				Airborne radiation: 0.2 mSv/y All exposure pathways combined: 0.5 mSv/y
Persons visiting or working at CERN who are not individually monitored	5 mSv/y	5 mSv/y	5 mSv/y	5 mSv/y
CERN personnel who are individually monitored	50 mSv/y	50 mSv/y	50 mSv/y	Routine activities: 15 mSv/y With special approval: 50 mSv/y

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[*] The expression ALARA comes from the wording As Low As Reasonably Achievable, contained in the ICRP recommendations.

These principles stipulate that all hazards will be kept as low as is reasonably achievable, taking social and economic factors into account. Observation of these principles is especially important for a project such as LEP, for which practically all the surface areas are public.

Persons working regularly in radiation-controlled areas

CERN personnel working under conditions where the possibility exists that their yearly dose-equivalent may exceed 5 mSv (500 mrem) will be supplied with individual dosimeters. They may work in the presence of radiation provided that they have medical clearance and are properly instructed. The limit for annual exposures for these persons is 50 mSv/y (5 rem/y; see Table 1). At CERN, a dose-equivalent exceeding 15 mSv (1.5 rem) in any given year requires prior approval by the Division Leader concerned. Such a dose-equivalent, distributed over a year's working time of 2000 h, corresponds to an average dose-equivalent rate of 2.5 μSv/h (0.25 mrem/h). This dose-rate limitation is the basic standard adopted for LEP shielding design for occupied areas.

Requirements for area and work control

All areas within the CERN fences are radiation-surveyed. Monitoring will ensure that the above limits are respected at the fence and beyond. In the unlikely event that the monitoring system shows that an exposure limit might be approached under continued operation, appropriate measures will be taken. These would include increased shielding or operation at reduced power, or both.

Areas where dose-equivalent rates in excess of 7.5 μSv/h (0.75 mrem/h) are expected during normal operation, and areas where annual dose-equivalents are likely to exceed 5 mSv (500 mrem) will be classified as radiation-controlled areas, and access will be restricted by appropriate warning signs and administrative controls.

Areas where annual exposure of workers may exceed 15 mSv (1.5 rem) will be classified as radiation-restricted areas, and access and working conditions will be controlled. Those who work regularly in radiation-controlled or radiation-restricted areas will be individually monitored and properly instructed and must have obtained medical clearance. Table 2 summarizes the categories of areas according to radiation dose rate.

Table 2

Radiation areas at CERN

			Type of area	Dose-rate limits (μSv/h)	Allowed annual max. dose (mSv/y)	Condition of access and work
			Public area (outside CERN fence)	2.5	5[a)]	Free access
Surveyed area			Surveyed area (all fenced CERN site)	7.5	5	Free access
	Controlled area		Controlled area (low risk)		50[b)]	Persons under the individual monitoring scheme must wear their personal dosimeter
		Restricted	Limited stay: medium risk	2000	50[b)]	Persons must wear their personal dosimeter; time restrictions.
			Highly restricted access: dangerous area	10^5	50[b)]	Persons must have special permission, an additional dosimeter, and warning devices.
			Forbidden area	$> 10^5$		No access[c)]

a) The CERN radiation protection policy statement limits the fence-post dose to 1.5 mSv/y (150 mrem/y).
b) Annual exposure must be kept below 15 mSv (1500 mrem/y) unless a higher exposure is authorized by the Division Leader in advance.
c) In very exceptional cases the Division Leader can authorize limited access to individuals after consultation with the RP Group Leader.

RADIATION PRODUCED BY HIGH-ENERGY ELECTRONS AND POSITRONS

The primary $e^\pm$ beams, when transported normally, are contained within the vacuum system and are therefore inaccessible. However, they can produce radiation which penetrates the vacuum chamber by two principal mechanisms:

a) When the $e^\pm$ strike the wall of the vacuum chamber, collimators, drift tubes, dumps, or other obstacles, a multitude of secondary particles and photons are emitted. This high-energy secondary radiation is mainly composed of e^-, e^+, and photons (the "shower" products), and to a much smaller extent it consists of neutrons, mesons, and other hadrons (see Figs. 1, 2)[3].

b) When accelerating or deflecting forces are exerted on e^+ or e^- they emit synchrotron radiation, with a photon spectrum determined by the particle energy and the deflecting or accelerating forces (see Fig. 3).

Most of the neutrons in LEP are produced by giant resonance interactions of high-energy photons. These photons stem mainly from the $e^\pm$ showers (bremsstrahlung), but at the highest LEP energies (γ,n) reactions are also initiated by γ from the synchrotron radiation. All estimates are based on a Monte Carlo simulation of the $e^\pm$, γ-showers[4,5] produced by the electrons in matter using well-known spectra, angular distributions, and reaction probabilities for these electromagnetic interactions.

Table 3 gives a qualitative description of the effects of the different radiation types.

In order to estimate the order of magnitude of all these components, the number of electrons and positrons interacting with machine components and the $e^\pm$ currents circulating in the main ring must be specified. Table 4 gives the beam losses for each of the accelerators in the chain and the maximum beam current expected for 86 GeV operation[6]. It is generally impossible to predict with certainty where these beam losses will occur. On the other hand, locations where synchrotron radiation hits the vacuum chamber are easily predicted, as this radiation is produced only in association with magnetic fields. Protection in the form of lead shielding has been designed and the intensity of the attenuated radiation is estimated with reasonable accuracy. Transport of the synchrotron radiation in the tunnel has been calculated with well-established and tested computer codes such as EGS[4] and MORSE[5]. Although synchrotron radiation is attenuated so easily that it is never a factor outside of the beam areas, it can cause severe radiation damage and activation within the LEP tunnel.

Based on the above parameters, the radiation problems will be discussed in the following paragraphs for each of the accelerators of the LEP project. Figure 4 shows the interconnection of the various accelerators comprising the LEP system. The highest beam losses occur in the Linear Injector for LEP (LIL) pre-injector, and the highest radiation levels are expected from synchrotron radiation in the main LEP ring.

THE $e^\pm$ LINAC AND THE ACCUMULATOR RING

The whole pre-injector system, consisting of the 200 MeV linac (LIL) (and its converter which produces the e^+), the subsequent linac to accelerate e^+ and e^- to 600 MeV, as well as the accumulator ring EPA for e^+ and e^-, will be built above ground, alongside the existing PS ring. It will be shielded by concrete and by earth over the injection tunnels leading to the PS (see Figs. 5 and 6).

Radiation protection measures are based on the assumption that the pre-injector is operated continuously in the dedicated mode, i.e. at the level of intensity needed to fill the main LEP ring. Several electron accelerators having this range of energy and intensity are now in operation, and the types of radiation produced are well understood. The required shielding for the LEP pre-injector has been calculated and is based on well-known parameters measured at similar installations elsewhere (Fig. 7).

The shielding is designed[7] to allow free access to the immediately adjacent area (less than 2.5 μSv/h or 0.25 mrem/h) when the machine is operating and producing the maximum radiation. The maximum dose rate anywhere outside the shield, even in inaccessible areas, will be limited to 1 mSv/h (100 mrem/h) in order to ensure that scattered radiation reaching occupied areas will always produce less than 1 μSv/h (0.1 mrem/h). These rather strict limitations are necessary owing to the close proximity of existing buildings and occupied areas. Because of the high degree of radiation containment planned for the pre-injector, and the relatively great distance to the site boundary, the radiation levels off-site from the pre-injector will be small; they are nowhere expected to exceed 0.2 mSv/y (20 mrem/y) at any point along the CERN fence[8].

In the framework of the LEP system it is planned to install 10 radiation monitors[9] in accessible areas near the pre-injector, in particular where radiation levels are expected to be higher and in areas where operating personnel are routinely present; higher radiation levels are expected near access ways and smaller openings.

Induced radioactivity can be produced in all parts of the pre-injector system. Estimates of the expected dose rates are given in Table 5 [10]. As can be seen the activation is slight, except in the vicinity of the converter target. Radioactivity will also be produced in the air and cooling water close to the target. The estimated air activity production rate [260 kBq/s (~ 7 μCi/s), mainly of 9.96–min N–13] can be considered low from the point of view of radiation protection[11]. In addition, the ventilation system will recycle the tunnel air, so that external irradiation due to activated air is expected to be insignificant. Similarly, the radioactivity content of the closed cooling circuits in the machine (estimated to be less than 100 GBq (~ 30 mCi, mainly of 2.05–min O–15), is such that no measurable radioactivity is expected to reach the CERN drains even in the event of a leak. Precautions are to be incorporated to minimize the dose rate from the heat exchanger of the converter cooling-water circuit.

Table 3

Qualitative nature of the radiations expected in LEP

Type of radiation	Consequences
Bremsstrahlung: When e$^{\pm}$ of beam strike components.	Electromagnetic cascade containing many secondary high-energy photons, electrons, and positrons; High-energy radiation, consisting of neutrons, hadrons (especially pions), muons; Radioactivity induced in components, air, and cooling water; Ozone and oxides of nitrogen produced in air.
Synchrotron radiation: When e$^{\pm}$ are deflected by magnetic fields.	Photons; typically of low energy. Neutron production. Radioactivity induced in components. Ozone and oxides of nitrogen produced in air.

Table 4

Assumptions made concerning beam currents and losses in the LEP injector and main ring

Location	Average current		Loss[a]	Average energy[a]	Average power (W)[b]	
	e$^+$	e$^-$	(%)	(MeV)	e$^+$	e$^-$
Output gun	–	5.5 μA	55	5	–	15
Output buncher	–	2.2 μA	10	100	–	25
Output 1st linac	–	2.2 μA	100	200	–	440
Output 2nd linac	18 nA	18 nA				
Output (resolved)	11 nA	11 nA	40	300	2.2	2.2
Output EPA	2.1 nA	2.1 nA	81	600	5.4	5.4
Trapped by PS	1.7 nA	1.7 nA	20	600	0.26	0.26
Trapped by SPS	1.4 nA	1.7 nA	20	3.5 × 10^3	1.2	1.2
Output transfer	1.2 nA	1.2 nA	10	20 × 10^3	5.6	5.6
Trapped by LEP	0.37 nA	0.37 nA	–	20 × 10^3	17	17
Colliding in LEP[b]	5.5 mA[c]	5.5 mA[c]	–	86 × 10^3	42 kJ	42 kJ

a) Except for first 3 lines, data describe losses estimated to occur at points *between* locations listed at left.
b) Power is averaged over 20-minute intervals, except for the last line, where the total energy (kJ) of circulating beams is given.
c) Current "colliding in LEP" is the total charge stored multiplied by 11 253 orbits per second.

Table 5

Dose rates expected (at 50 cm from the pre-injector) from induced radioactivity

Location of induced activity	Dose rate in mSv at 50 cm			
	1 h after stop		1 day after stop	
	Iron	Copper	Iron	Copper
1st linac	0.20	0.13	0.07	0.015
Converter	15	9	6	0.90
2nd linac	0.02	0.01	0.01	0.002
2nd linac (dump)	0.25	0.13	0.09	0.013
EPA ring	0.05	0.03	0.02	0.003
PS ring	0.01	0.006	0.004	0.0006

A further source of low-energy X-radiation is the klystrons installed above the linac. The klystron gallery will be classified as a Radiation-Controlled Area and will be accessible to personnel during operation only under suitable control. Such access would require efficient shielding against X-rays produced by the klystrons during formation and routine operation. This shielding is provided by the manufacturer according to CERN specifications and is routinely checked at the time of installation. During operation at maximum power, dose rates at 10 cm from the outer accessible surface will be less than 2.5 μSv/h (0.25 mrem/h).

Final boundaries to Radiation-Controlled Areas will be determined when radiation levels have been measured. In the planning stage, it is envisaged that, apart from the beam areas, only the klystron gallery will be declared a "Radiation-Controlled Area". In summary, the essential elements comprised by the pre-injector radiation protection system are: the shielding configuration, the containment of radioactive air and cooling water, and the radiation monitoring system. Operational radiation protection will be entrusted to the local PS Radiation Protection Section, which is equipped to cope with any possible radiation problem in this area.

THE PS AS ELECTRON–POSITRON ACCELERATOR

The accelerator system of the PS will be modified to permit acceleration of $e^\pm$ from 600 MeV to 3.5 GeV. Radioactivity and stray radiation in the PS will arise whenever electrons are lost from their orbits; these losses are estimated as 20% of the injected $e^\pm$ (Table 4). The secondary radiation from the $e^\pm$ interacting in the PS is so low that it will not measurably increase the average radiation levels outside the existing PS shielding tunnel. The radioactivity produced in the PS is less than 0.1% of the proton-induced activity, and the existing PS protection system will cover all radiation problems from this additional high-energy radiation source.

The synchrotron radiation produced by circulating $e^\pm$ has a critical energy*) at 3.5 GeV of 1.36 keV and a total power loss of about 1 kW for a 5 mA circulating current (combined e^+ and e^-). The fraction of synchrotron radiation which can penetrate the PS vacuum chamber (stainless steel) is negligible, and heating of the chamber in the curved sections (440 m long) with about 2.5 W/m is too small to be of any concern.

The radiation protection system for the PS in the dedicated LEP-filling mode is entirely covered by the existing facilities.

THE SPS AS LEP INJECTOR

Electrons and positrons transferred from the PS to the SPS via the transfer tunnels TT70 and TT10 at 3.5 GeV will be accelerated in the SPS to 20 GeV (or more) and then extracted and transported to the LEP main ring. About 20% of the $e^\pm$ are expected to be lost in these operations. These $e^\pm$ interact with accelerator components and produce secondary radiation and some radioactivity. The prompt radiation is completely absorbed by the massive shielding above the transfer tunnels and the main SPS ring; the intensity is so low that even in adjacent areas the radiation levels will be insignificant — at least a factor of 1000 lower than for proton operation. Existing shielding, monitoring systems, and access control systems are therefore more than adequate for controlling the prompt radiation, including the synchrotron radiation.

Furthermore, the total amount of radioactivity produced by $e^\pm$ is orders of magnitude lower than the activity induced by proton operation of the SPS. This statement also applies to the radioactivity produced in air and cooling water as well. Control measures already implemented at the SPS cover all such problems.

The synchrotron radiation produced in the SPS by $e^\pm$ in the energy range from 3 to 25 GeV has been extensively studied and the effects on materials assessed[12]. The energy loss per metre in a bending magnet of the SPS and the associated critical energy are shown as functions of electron energy in Fig. 8. Parameters for assessing the effects of synchrotron energy in the SPS are listed in Table 6.

Since the critical energy is a strong function of electron energy, the magnitude of radiation effects will vary greatly within an e^+ e^- acceleration cycle. Therefore, as a simplification, it is assumed that one complete e^+e^- cycle is equivalent to 50 ms of electron operation at 20 GeV.

Dose to SPS magnet insulation

Primary synchrotron radiation produced in the dipole magnets of the SPS impinges on the stainless-steel vacuum chamber, at a small angle of about 15 milliradians, where most of it is absorbed. Assuming an annual operation of 5×10^5 $e^\pm$ supercycles ($= 10^5$ s), the scattered dose to the coil insulation in the horizontal plane is about 7×10^2 Gy/y (7×10^4 rad/y) for an MBB-type magnet (1.5 mm thick vacuum chamber) and about 3.5×10^2 Gy/y (3.5×10^4 rad/y) for an MBA magnet (2 mm thick vacuum chamber). Outside the dipoles the synchrotron radiation can penetrate perpendicularly through the 1.5 mm thick vacuum chamber and could irradiate the coil of the adjacent magnet with almost no attenuation. A lead collar, 10 mm thick, reduces the dose to the coil ends to 20 Gy/y (2000 rad/y) for

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*) The critical energy $\varepsilon_c = 2.2 \times E^3/\rho$ (ε_c in keV, E in GeV, ρ in m) divides the synchrotron spectrum into two halves with respect to radiated power.

Table 6

Parameters describing synchrotron radiation as produced in the SPS

Maximum energy of (e^+,e^-) beams	20 GeV
Number of electrons or positrons per SPS pulse	6.4×10^{10}
Mean radius of SPS	1100 m
Current in the SPS (each beam)	0.445 mA
Bending radius of main ring magnets	741.3 m
Energy loss for a single electron per turn	19.1 MeV
Energy loss per metre of dipole	4.1 keV/m
Power loss per metre of dipole	1.82 W/m
Critical energy of synchrotron spectrum	23.9 keV
Super period of SPS magnet cycle	15 s
Number of e^- cycles per superperiod ($2e^-$, $2e^+$)	4

20 GeV operation. For 22 GeV operation, the dose from synchrotron radiation rises to 600 Gy/y (6×10^4 rad/y). For proton operation in the SPS the "average" dose to the magnet insulation is actually of the order of 10^4–10^5 Gy/y (10^6–10^7 rad/y); similar doses from synchrotron radiation would be reached above 25 GeV.

Production of ozone and nitric acid

Calculations made using the Monte Carlo programs MORSE and EGS confirm that the dose received by the air in the bending magnets between the vacuum chamber and the coil insulation is close to that received by the superficial layer of the insulation itself. Averaged over the full height of the magnet gap, this leads to an energy deposition in the air of 8.3×10^9 eV/cm^3 for each second of beam circulating at 20 GeV, or 3.34×10^8 eV/(cm$^3 \cdot$s) averaged over the whole of a LEP fill.

Assuming that electron acceleration in the SPS continues for longer than the normal dissociation time of the O_3 molecules (approximately 30–50 min), one arrives at 4×10^{-3} ppm of O_3 equilibrium concentration. For comparison, the tolerable concentration for human exposure is 0.1 ppm.

The irradiation of air forms various oxides of nitrogen which combine with the water vapour of the air (which is always present in sufficient quantities) to form acids of nitrogen. The nitric acid concentration after one LEP fill of 20 min will be

$$2.2 \times 10^{-4}\ \text{ppm}\ HNO_3 .$$

The effect of this on the SPS vacuum chamber is not known directly. However, no effects have been directly attributable to nitric acid produced by the present irradiation of the vacuum chamber by protons at an annual rate several orders of magnitude higher than that calculated in the present paper. It can therefore be safely assumed that nitric acid produced by electron acceleration will not be of importance.

Apart from the addition of lead collars in selected places, the existing radiation protection system for proton operation in the SPS seems fully adequate for e^+e^- acceleration[13].

THE MAIN LEP RING

Radiological impact on the environment

Except for the eight fenced islands around the LEP access points, the surface area will be freely accessible to members of the public, and customary activities, such as agricultural and residential uses, will continue (Fig. 9). In assessing the environmental impact, it is primarily the release of radiation and radioactivity to areas not under control of CERN that is of concern.

The impact due to any such release, including radiation-produced noxious gases, has been studied extensively for an earlier LEP design in which the main ring was located further under the Jura and a maximum beam energy of 125 GeV was envisaged[14]. The radiological impact was shown to be insignificant and no nuisance from stray radiation or release of noxious gases was expected. Subsequent revisions in the LEP design have not given any cause to change this conclusion. The data discussed below are based on the now-approved design, "LEP version 12".

Release of stray radiation

The LEP ring will be situated at such a great depth that direct penetration of high-energy radiation to surface areas above ground can be disregarded. Furthermore, a muon of the maximum possible energy (85–100 GeV) would easily be stopped ("ranged out") by the natural shielding of earth and rock, which is more than adequate in all directions within the median plane. The production mechanism of muons is such that they will follow almost exactly the path of the primary $e^{\pm}$ that produced them and, therefore, the paths of all muons produced must remain very close to the plane of the ring. An imaginary "radiation cone" of 100 milliradian half-angle about any axis tangential to the ring would not penetrate the natural terrain for at least 6 km. This distance is many times greater than the maximum muon range.

On the other hand, scattered radiation might reach the surface through access shafts or tunnels, and these penetrations must be carefully located and possibly shielded from radiation sources. These penetrations are located in straight sections of the main ring, where only weak synchrotron-radiation sources, such as quadrupole magnets, are located. In addition , shielding is provided between these radiation sources and the access shafts. An estimate of the radiation levels at the top of an experimental equipment shaft gives an annual dose due to scattered radiation well below 10 μSv/y (1 mrad/y), i.e. not detectable above the natural radiation level of about 800 μSv/y (80 mrad/y).

The radiation protection system will also provide for monitors in the underground areas. The control of radiation levels at ring level will also automatically limit the amount of stray radiation released.

Release of radioactivity with water

Radioactivity is produced in the cooling-water circuits by high-energy radiation and by the high-energy tail of the synchrotron radiation spectrum. Radioactivity may also be produced in ground water outside the main-ring tunnel, or leached out from activated rock or soil by the ground water.

Ground-water activation can only occur when the water is in close proximity to the concrete main-ring tunnel. However, most of the ring is drilled in molasse, which is waterproof and dry, as extensive experience with the construction of the SPS has shown. In the Jura formation (about 5 km of the ring), water could penetrate near the tunnel. However, the total activity production expected in the rock and water is so small that even a 100% leaching would result in only an insignificant increase of the natural water activity (see Table 7). Because of the small amount of activity induced, the dilution by other sources, and the time delay, the possible migration and ultimate use does not produce any impact on the environment nor is there any risk to persons who may ultimately use this water.

Table 7

Total radioactivity in water and rock in and around the main LEP ring*
[(T): tritium]

	Natural activity	Activity produced by LEP at 100 GeV
Rock around the main ring, 1 m thick layer	200 GBq	0.4 GBq
Water "around" the main ring	–	0.2 GBq(T)
Annual rainfall over 10 km^2	200 GBq(T)	–
Cooling-water circuits	0.2 MBq(T)	0.2 GBq

*) 1 Bq = 2.70 × 10^{-11} Ci.

The cooling systems will be closed circuits and no release is expected in normal operation. When the circuits are drained (during repair or by accident) the cooling water will be collected in the general ring-drainage system, from which it will be pumped and collected. The values in Table 7 show that even a total loss of beam in one ring-octant will not significantly contaminate the large amount of waste water released from LEP. Water will be periodically sampled at the deepest point in the ring (near Access Point 8; see Fig. 9) and monitored for activity before release. If needed, release from the ring drains can be held up for a considerable time, as the capacity of the drains is large — more than 200 m^3 per octant. In case of flooding, water can be pumped out immediately, as dilution will reduce activity concentrations to negligible levels.

Radioactivity and noxious gases released with air

Although the gaseous isotopes in the exhausted air may lead to external exposure of persons in the most unfavourable location, this risk has been shown to be insignificant. At 100 GeV operation the production of radioisotopes (such as ^{13}N) by synchrotron radiation sets in (production threshold 15 MeV), and adds to the very small production by high-energy particles. Table 8 shows the results, assuming that all $e^{\pm}$ of the beam interact in unshielded regions of the ring, giving the greatest possible exposure to the air.

The radiation protection system provides, firstly, for adequate shielding of the vacuum chamber in order to reduce the amount of synchrotron radiation escaping into the air; in this way it reduces the production of both radioactive and noxious gases. Secondly, the system provides for a minimum height of the release point and for a minimum vertical release velocity. Besides these protective measures, the radiation protection system will provide for air monitoring both in the stack and at the critical distance at ground level (200–500 m).

Table 8

Radioactivity released by air (per year)*)

LEP energy (GeV)	Specific activity (kBq/m^3) Synchrotron radiation	High-energy radiation	Total	Relative production of isotopes ^{13}N (%)	^{15}O (%)	Annual release (GBq)
51.5	–	0.90	0.90	85	14	850
86	0.04	1.40	1.44	87	12	1300
100	1.80	1.80	3.60	95	5	4000

*) 1 Bq = 2.70 × 10^{-11} Ci.

The requirement of maintaining the ground-level concentrations around the release points as low as can reasonably be achieved, imposes some conditions on the LEP ventilation system:

- the minimum height of the release point must be either 10 m above ground level or 2 m above the roof level of the access buildings, whichever is higher;
- the vertical velocity of the ejected air at the mouth of the release point must be at least 10 m/s in order to obtain a reasonable effective chimney height.

With pessimistic assumptions concerning the dispersion of the active air after release[15] we obtain, in the main wind direction, maximum ground level concentrations of 4 Bq/m^3 for operation at 100 GeV. During an annual operating time of 3000 hours, and adopting a conversion factor of 40 kBq/m^3 = 10 μSv/h (1 mrad/h) for the submersion dose (from the isotopes ^{13}N, ^{15}O, ^{11}C, and ^{41}Ar combined), we arrive at 3 μSv/y (0.3 mrad/y) as the maximum possible dose to a member of the public living in the most critical location (a distance of 200–500 m) near a release point (Access Points Nos. 1, 3, 5, 7; see Fig. 9). It should be noted that the half-lives of these isotopes are relatively short, especially for those most copiously produced: 9.96, 2.05, 20.34, and 109.8 min for ^{13}N, ^{15}O, ^{11}C, and ^{41}Ar, respectively. Thus, even if larger amounts were released, no lasting effect would result.

The concentrations of noxious gases such as O_3 and NO_x are also the highest where the maxima for activity are expected. Of these gases, it is ozone (O_3) which has the smallest limit of permissible concentration and which also is the most copiously produced. It is therefore the limiting consideration and both its instantaneous and long-term average concentrations must be considered. All LEP-produced concentrations will remain well below existing natural concentrations. Table 9 gives the maximum concentrations of LEP-produced O_3 and NO_2 that might be found in the vicinity of a release point. These can be compared to the upper limit of 0.1 ppm for continuous human exposure to O_3.

Table 9

Maximum concentrations of O_3 and NO_2 at 200–500 m from LEP release points

LEP energy (GeV)	Maximum concentrations (ppm) O_3	NO_2
51.5	7×10^{-6}	4×10^{-6}
86	0.0013	0.0016
100	0.005	0.0025

Environmental monitoring programme

Although all studies of the environmental impact consistently predict unmeasurably low radiation, radioactivity, and noxious gas levels, the radiation protection system provides for confirmation of these low levels by environmental measurements. The programme, outlined in Table 10, is designed to monitor all possible environmental contaminants. Detectors are specified to be sensitive enough to measure natural background levels to within ±10% precision. A development programme is foreseen with the initial aim of establishing pre-operational background levels more

Table 10

Elements of the environmental monitoring programme

Monitored subject	Kind of radiation, radioactivity	Measuring instruments	Locations	No. of points	Frequency
1. Ambient radiation doses	Total γ Total n	Argon-filled ionization chamber and moderated BF_3 counter	Near shaft No. 5 (France)	1	Continuously
			Near shaft No. 1 (Switzerland)	1	
	Total γ Total n	TLDs (1 ^{6}LiF/^{7}LiF) + (1 CaF_2:Dy)	Near shaft No. 5 (France)	5	1 × per year (LiF)
			Near shaft No. 1 (Switzerland)	5	4 × per year (CaF_2)
	Soft and hard components of cosmic radiation, radioactivity in air and soil	Argon-filled ionization chamber	Near shaft No. 5 (France)	1	(~ 4 × per year)
			Near shaft No. 1 (Switzerland)	1	
			Other places of interest for special studies		
	γ-emitting isotopes in air and soil (*in situ* measurements)	Ge(Li) diode	Near shaft No. 5 (France)	1	(~ 2 × per year)
			Near shaft No. 1 (Switzerland)	1	
			Other places of interest for special studies		
2. Aerosols	Total β	Large-area prop. counter	Near shaft No. 5 (France)	1	Continuous sampling, filter change 2 × per year
	γ-spectrometry	Ge(Li) diode	Near shaft No. 1 (Switzerland)	1	
3. Surface water	Total β	Large-area prop. counter	La Versoix	2	4 × per year
			L'Allondon	1	4 × per year
	γ-spectrometry	Ge(Li) diode			
	^{40}K	Flame photometer			
	^{3}H	Liquid scintillation counter			
4. Tap and underground water	Total β	Large-area prop. counter	Commune of Versonnex	1(2)	4 × per year
	γ-spectrometry	Ge(Li) diode	In LEP tunnel		If water is found
	^{40}K	Flame photometer			
	^{3}H	Liquid scintillation counter			
5. Soil	Total β	Large-area prop. counter	Near shaft No. 5 (France)	1	2 × per year
	γ-spectrometry	Ge(Li) diode	Near shaft No. 1 (Switzerland)	1	
	^{40}K	Flame photometer	Other places of interest for special studies		
6. Grass and vegetation	Total β	Large-area prop. counter	Near shaft No. 5 (France)	1	1–2 × per year
	γ-spectrometry	Ge(Li) diode	Near shaft No. 1 (Switzerland)	1	
	^{40}K	Flame photometer	Other places of interest for special studies		
7. Fish	Total β	Large-area prop. counter	La Versoix	1	1–2 × per year
	γ-spectrometry	Ge(Li) diode	Le Lion	1	
	^{40}K	Flame photometer			

precisely. It is expected that none of the levels outside the boundary fences will change significantly from the initial background levels, even when LEP is operating at full design intensity at 100 GeV.

Stray radiation and dose from exhaust plumes will be measured by ionization chambers and/or Geiger–Müller counters, Andersson–Braun neutron counters, and by gamma- and neutron-sensitive TLD monitors[16,17]. Air activity is also measured in two exhaust stacks; the gaseous beta–gamma activity by *in situ* GM counters and TLDs and the aerosol activity by analysing exhaust filters in the laboratory. Aerosol samples will also be taken in locations where the maximum ground-level concentrations are expected. Concentrations of $O_3$and NO, NO_2 are monitored in the stacks and also at ground level[18,19].

Activity in the water will be monitored by two continuously operating stations to check specific activities of both incoming and outgoing water. In addition, samples from the ring and heat exchangers, and from a number of points in rivers and the water supply systems of the area, will be analysed in the low-level counting laboratory (see Fig. 9).

RADIATION PROTECTION IN UNDERGROUND AREAS

Primary beam areas

Access to primary beam areas during operation

Very high dose rates are expected within the main LEP tunnel, particularly in the curved sections, as shown in Tables 11 and 12 (see Fig. 10). These doses arise from two different fundamental mechanisms: synchrotron radiation and high-energy radiation. The synchrotron radiation occurs where the beam particles undergo transverse deflection. This occurs primarily in dipole magnets of the curved sections but also, to a lesser extent, in focusing (quadrupole) magnets. Some of these are located in straight sections. By the nature of synchrotron radiation, the dose rates in these areas will be of a steady, predictable nature that is easily calculable for a given value of beam current and magnetic field. Table 12 shows estimated dose rates in the LEP tunnel passageway.

On the other hand, high-energy radiation is produced only when the stored $e^{\pm}$ beams hit the walls of the vacuum chamber. Such an event can occur accidentally; for example, when a magnet power supply fails or if the beams are mis-steered for any other reason. In this case the momentary dose rates will be very high in the immediate vicinity of the beam-loss point. The dose integrated over the time of such beam loss will be in the range 0.01–1 Sv, at 1 m distance, depending on how the beam is actually stopped. It is also possible that the beam is slowly lost over a period of time; Table 11 shows the dose rate in the tunnel passageway during a period of beam loss assumed to extend over 160 minutes.

Because of these possible high dose rates, all primary beam areas, including the LEP tunnel, are considered Prohibited Radiation Areas and access is not possible during operation. The access-control system prevents accidental access and shuts off the accelerator in case doors are forced. The degree of safety is enhanced by the fact that access to the areas adjacent to primary beam areas is also controlled. (For definition of radiation areas, see Table 2).

Table 11

Dose in main LEP tunnel from high-energy interactions of e^+, e^- at 86 GeV
(assuming currents of 5.5 mA e^+ plus 5.5 mA e^-, or 3×10^{12} each of e^+ and e^-).

Beam loss condition (no shielding assumed)	Dose or dose rate at 1 m, due only to e^+, e^- interactions
All beam lost at 1 point	2.40 Sv
All beam lost at 1 point within 160 min[a]	0.90 Sv/h
Half of total beam lost at 8 points over 160 min	0.06 Sv/h
All beam lost over 160 min uniformly around circumference	25 μSv/h

a) 160 minutes is the expected lifetime of beams.

Protection measures in the primary beam areas

In the primary beam tunnel, which is inaccessible during operation, all equipment is exposed to synchrotron and high-energy particle radiation. The latter, averaged over longer periods, is very low compared to the radiation resistance of most components, but the synchrotron radiation in curved sections and near quadrupoles produces high dose levels.

According to the agreed acceptability criteria, the components must remain fully operational after having been exposed in the ring to radiation produced during the course of operation equivalent to 200 A·h of beam at an energy of 86 GeV. The dose values in critical locations near dipole bending magnets for such an irradiation are given in Table 12. The corresponding values for 100 GeV beam energy are 2–3 times higher.

Table 12

Synchrotron radiation doses in LEP tunnel (in the vicinity of dipole magnets) produced by 200 A · h of beam at 86 GeV, with the lead shielding arrangement described in the text. Doses at 100 GeV will be two to three times higher.

System or component	Basic radiation-sensitive component	Dose limitation assumed (Gy)	Calculated dose (Gy)
Dipole magnet:	Glass-fibre-reinforced epoxy resin		
inner coil		5×10^7	6×10^6
outer coil		5×10^7	3×10^5
Quadrupole magnet:			
coils	"	5×10^7	1×10^7
Magnet connections, such as bus-bars, hoses, etc.	Various thermoplastics	1×10^6	2.5×10^4
Cable trays:			
top, side	EPR, polyolefins	1×10^6	2×10^4
Electronic equipment under magnets	Various	10^2–10^4	1×10^4
Aux. equipment in passageway	Telephone, crane	1×10^6	5×10^5
Tunnel lighting	Fluorescent tubes	1×10^6	1×10^5
Air in tunnel (average)	(Noxious gas production; see text)	-	2.5×10^5

The entire aluminium vacuum chamber within the bending and quadrupole magnets, in the inter-magnet gaps, and along the straight sections and most of the long straight sections is provided with a continuous sheath of lead shielding (Fig. 11). The lead thickness is 3, 6, or 8 mm, depending on its location, and reduces the radiated power by 98–99%.This shielding is one of the primary measures of the radiation protection system, as it reduces not only the doses to components but also the production of noxious gases and radioactivity in the air[20]. It is a reasonable compromise, taking into account the available space, weight, and fabrication requirements.

Production of O_3 and NO_x in air is reduced by means of the lead shield, and a minimum ventilation speed helps to avoid pockets of high concentration near the vacuum chamber. Protective paints will be applied to reduce corrosion of machine components. For sensitive equipment, shielded alcoves will be provided in which doses can be kept below 10 Gy (10^3 rad) for 200 A · h of operation.

While LEP is in operation, the predicted concentrations of O_3 and NO_x in the tunnel are in excess of the legal standards for workers. However, as explained above, the LEP ring is a Radiation-Prohibited Area and will not be occupied during operation.

Access to main ring during shutdown

For operation at 86 GeV the total inventory of remanent radioactivity is so low in the LEP ring that dose rates will be below 2.5 μSv/h (0.25 mrem/h) in most areas of the tunnel. Only for 100 GeV operation, and only for those components most directly exposed to synchrotron radiation, will induced activity be significant. Even in this worst case the dose rates will only be of the order of 10 μSv/h (1 mrem/h) at a working distance of 40 cm, and special precautions will be required only for dismantling and maintenance operation. Table 13 summarizes the information on predicted activity and contact dose rates at 20, 86, and 100 GeV.

Even though the potential radiation exposure to personnel entering the LEP tunnel is small, access control will nevertheless be required and a reasonable waiting time will be imposed for air renewal. This is because the enormous length of the tunnels makes it extremely difficult to search them again for personnel before recommencing operation. There are also administrative reasons for such access control, owing to the location of LEP on the French–Swiss

Table 13

Total activity (at saturation) and contact dose rates of accessible components most susceptible to activation at different operating energies

Component (material)	Unit*)	Operating energy (GeV)		
		20	86	100
Activity in entire machine	GBq	-	4	1200
Activity in magnets (Fe)	GBq	-	3	1000
Activity in vacuum chamber (Al)	GBq	-	0.1	0.1
Activity in Pb shielding	GBq	-	0.15	160
Dose rate in contact with Pb shielding	mSv/h	-	$< 10^{-2}$	< 10
Activity in Cu from continuous beam loss of 1 W	GBq	0.8		
Dose rate in contact with tank of cavity	μSv/h	10–100		

*) $1 \text{ Bq} = 2.70 \times 10^{-11}$ Ci.

border. As for all LEP underground areas, access control will provide for registration of name, time, and door location. Figure 12 shows the type of entrance facility to be used for radiation-controlled areas.

Underground service areas

Protection in service areas

The service areas, including the access shafts and tunnels, and klystron galleries are all separated from the main ring and interaction areas by a minimum shielding equivalent to 2 m of concrete. Shielded doors will be provided for equipment access penetrations, and either shielded doors or labyrinths for personnel access and ventilation ducts, etc. Detailed dose calculations have been made for the klystron galleries and access ways to the main ring[21]. The efficacy of shielding is such that only in very localized regions (a few square metres) are dose rates in excess of 10 μSv/h (1 mrem/h) predicted; for normal operation the dose rates from the accelerator will be below 2.5 μSv/h (0.25 mrem/h) in the work area if the ducts are blocked with the duct shielding envisaged.

In order to monitor possible accidental situations that might arise from beam mis-steering during injection, a monitor system will be installed in areas adjacent to the primary beam areas. These monitors are linked to the Radiation Protection (RP) data-acquisition system and LEP control system.

The ventilation system for the service areas is separated from the ring ventilation system, to eliminate the possibility of air contamination in these areas from radiation-produced noxious or radioactive gases.

Access to service areas

The access control system for the underground areas will be installed at the top of the access shafts. All persons entering (including accompanied visitors) must register at the door (Fig. 12). Name, time, and location are logged in by means of personal access cards. Personal dosimeters (film badges) will be required during times of LEP operation.

The klystrons in the klystron galleries are also sources of radiation. Radiation levels due to insufficiently shielded klystrons could be higher than the radiation from the main ring in these areas. Each klystron is individually shielded by the manufacturer, and the requirements specify a dose rate of 2.5 μSv/h (0.25 mrem/h) or less, at 10 cm from the accessible surface. However, during testing or routine operation, klystron shielding might be inadvertently removed. To prevent doses to personnel under these circumstances, a shielding interlock will be provided on each unit, as well as radiation monitors for each gallery. By these means, it is expected that the dose accumulated by the service staff will be less than 1 mSv/y (100 mrem/y) for all these areas.

RF radiation in the klystron galleries with intensities above recommended limits*) is possible only if, after maintenance or repair, the waveguides are not tightened or whole parts of the waveguide are left out. Inspection and tests before power is applied are required.

Experimental areas

Shielding philosophy

Dose rates expected in experimental areas within the interaction regions have been estimated[22,23] and it was found that a minimum shielding of 1.2 m of concrete (or the equivalent of some other material) is needed to reduce the dose rates to below 10 μSv/h (1 mrem/h). If the bulk of shielding is made of steel, some material containing hydrogen (organic, concrete) must be added to reduce the neutron fluence.

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*) 10 mW/cm^2 for continuous exposures over 1 hour and 1 mW/cm^2 for 40 hours a week in the frequency band of 10^7–10^{12} Hz.

Owing to the massive size of the detectors and the requirement of keeping cable connections short between detector and electronics, it was decided to achieve the required shielding by means of the detector components themselves. For the experimental areas, only high-energy radiation from the $e^{\pm}$ interactions need be considered. It is evident that owing to these design constraints, dose rates in excess of 10 μSv/h (1 mrad/h) are possible in accessible areas under conditions of beam mis-steering. The philosophy of incorporating the shielding in the detector implies a more elaborate system of design review and coordination between the Radiation Protection Group and the experimenters than would a simple fixed-shield concept. Each detector concept must be carefully designed and studied before approval for installation can be granted.

Radiation protection for experimental areas

In order to restrict access to experimental areas to personnel familiar with the risks, or to visitors escorted by such personnel, the interaction regions will be designated Radiation-Controlled Areas (see criteria, Table 2).

Before installation, each experiment must provide shielding specified by the Radiation Protection Group. In addition, radiation surveys will be required both in the checkout stage and for routine operation. A permanent radiation monitoring system will also be employed, consisting of both passive (TLD) and active monitors[9]. The active monitors (a minimum of three for each experimental area) will be connected on-line to the RP data-acquisition system and to the experimental control centre. The data-acquisition system provides for continuous readout of instantaneous dose rates and also develops a "history" of the radiation levels of each instrument, which can be conveniently retrieved from the system. The monitors are of conventional design and have already been in use at the existing CERN accelerators[24].

With the exception of limited areas very close to the detector, it is expected that dose rates will be well below 10 μSv/h (1 mrem/h) in most areas of the interaction regions (< 2.5 μSv/h). Experimenters are likely to receive doses of the order of 0.5–5 mSv/y (50–500 mrem/y) in the LEP areas (Fig. 13). Although such doses are in the range that would be acceptable to members of the general public, many of the experimenters also handle radioactive sources and work around test beams of other accelerators. Therefore, all members of each experimental team must be given clearance to work with radiation and must carry a personal dosimeter. The large sensitive LEP detectors require that the background radiation be kept extremely low, and it can be expected that special care will be taken to keep the number of interactions of beam particles with the walls of the vacuum chamber and other components as low as possible. As the experiments are located in straight sections, synchrotron radiation will be at a minimum. Therefore, the amount of remanent induced activity will also be very low and the need for any special precautions for protecting experimenters from this potential radiation source is not anticipated.

INSTRUMENTATION

An important element of the radiation protection system is the complement of instruments provided and maintained by the Radiation Protection Group to monitor and measure radiation and to warn those exposed of unexpected levels. The monitor system also provides a record of the release of prompt radiation, radioactivity, and noxious products to the environment. Levels at the fence and at critical locations outside the fence are continuously monitored (see Fig. 9).

Water release monitors

Water monitoring is provided by the existing system in SPS Auxiliary Building 6. Here the water released from the SPS, and in the future from LEP (Access Point 1), passes through a continuously operating water monitor consisting of a 3″ long × 3″ diameter NaI(Tl) detector immersed in an 0.8 m^3 tank. The total gamma activity (0.2–2.0 MeV energy range) and gammas near the positron annihilation energy (0.511 MeV) are recorded. This provides high sensitivity for the measurements of all positron emitters (limit of sensitivity ~ 4 Bq/l).

In parallel with the continuous monitor, an automatic sampler takes water samples every 4.8 min for separate beta and gamma analysis in the low-level laboratory. Special samples will also be taken for analysis prior to release when water from the main-ring cooling system is drained.

Air monitoring system

Air from the main LEP ring ventilation system is released via four stacks (see Fig. 9). Continuous monitoring of the air for beta activity will be performed in a bypass to the main release duct at Access Points 1 and 5. Owing to the symmetry of the LEP ring, the concentrations of activity and radiogenic noxious compounds are assumed to be the same at the other Release Points 3 and 7.

At Access Point 1 (on Swiss territory) and Access Point 5 (in France, far from other CERN installations), some of the released air will pass through a short bypass in which two Geiger–Müller tubes will measure the beta and gamma activity. The air passes through a filter in which the aerosols are retained for later analysis in the low-level laboratory. Separate detectors for O_3 and NO–NO_2 are installed in the same bypass. The volume of air ejected through the bypass and release points is measured so that concentrations of possible contaminants can be determined.

Environmental monitoring

The monitoring programme requires the laboratory analysis of many samples taken from around the LEP site and in the surrounding areas. The instrumentation is identical to that already in use for CERN environmental measurements[16)]. Continuous monitoring equipment will be installed at suitable locations near LEP facilities. Stations for measuring radioactivity and noxious gases at locations beyond the site boundary will be provided near Release Points 1 and 5 (Fig. 9).

Calculations have shown that under present average release conditions the maximum ground-level concentrations are expected at a distance of 200 to 500 m downwind from a 10 m high release point. In the Pays de Gex, the two dominant wind directions (SW and NE) are nearly equally probable. It is therefore planned to have a station 300 to 400 m north-east of Access Point 1 and the second station 300 to 400 m south-west of Access Point 5 (see Fig. 14). They will contain a stray-radiation monitor consisting of a highly sensitive ionization chamber and an Anderson–Braun neutron counter. There will be an air sampler of the same type as in the release monitors, and O_3 and NO–NO_2 detectors for continuous monitoring. These detectors will be conventional ones based on chemical luminescence and will contain *in situ* calibration facilities.

Two meteorological stations are combined with the radiation-monitoring stations for measuring wind direction and speed, and also temperature and rainfall. It is intended that the meteorological parameters be continuously recorded. This history of environmental conditions is essential for evaluating the consequences of releases from LEP.

Underground monitoring system

Monitors in the LEP underground areas will provide protection for maintenance teams in service areas adjacent to the main ring. Because neutrons may be present along with high-energy electromagnetic radiation, plastic-walled ionization chambers will be installed as detectors in the klystron galleries and service tunnels. The chambers are equipped with charge digitizers, and are linked to control units (data loggers) where alarms are generated if the radiation rises above a pre-determined level. The data loggers also receive signals from the experimental-area monitoring system and the environmental stations.

Displays for radiation warnings which will be triggered by the monitors will be installed in the klystron galleries, the experimenters' control areas, and at the bottom of the service shafts.

Data-acquisition system

All monitors to be installed for LEP are compatible with the standard RP data-acquisition system control and transmission interfaces (Fig. 15). The data loggers will transmit the information from the detectors to the data-acquisition system. From the associated data base (two NORD-100 computers linked to LEP/SPS and PS control systems), the instantaneous and accumulated information will be accessible to the Radiation Protection Group, the operations team, and the LEP experimenters via remote terminals. The data-acquisition system, linked to the RP alarm and instrument-surveillance system will provide the relevant information to those who need it.

Survey and intervention instrumentation

The types of instruments currently used by the RP technicians around the proton accelerators are also quite suitable for use at LEP. A radiation-protection station is required at each shaft in the access buildings to house the survey instruments and other radiation-protection materials, such as ropes, signs, and materials for taking samples. In addition, two mobile laboratories equipped with instruments and radiation-protection materials will be provided. Ten additional sets of portable survey instruments, including those for the mobile stations and mobile ring survey monitors on the mobile crane (monorail), would be adequate to cover the needs of LEP.

COSTS

The radiation protection system, as defined here, comprises many items in addition to those readily identifiable as such. The design of many components is influenced by considerations of radiation damage and potential for induction of radioactivity. It is therefore difficult to give a financial accounting of all aspects of the radiation protection system as described in this report.

For budgetary planning, the financial estimates given here cover only those elements of the system provided by the LEP Radiation Protection Group. The total of new investments (at 1982 prices) is estimated to be about 3 million Swiss francs. From this figure the approximate yearly additional operating cost is estimated to be 250000 Swiss francs. As the CERN Radiation Protection Group operates at present, personnel costs represent about 75 to 80% of the total operating cost. A reasonable extrapolation of past experience to LEP, whose radiation problems are much less severe than those of the existing proton accelerators, would suggest that $\sim$ 12 man-years/year are needed to operate radiation protection at LEP. At 1982 prices the costs would be about 1 million Swiss francs for personnel plus 0.3 million Swiss francs for material. These estimates include costs of environmental monitoring, technical support, material-testing and high-level dosimetry for components, as well as overhead expenses for the Radiation Protection Group.

CONCLUSIONS

The proposed radiation protection system is completely adequate for controlling all radiation problems related to LEP. In particular, the environmental effects are extremely small, and the environmental measurement programme will demonstrate the absence of any risk outside the confines of CERN. Those who have access to underground areas will be sufficiently protected against any direct radiation or radioactivity produced in LEP. Compared with experience at the proton accelerators, personnel doses will be considerably reduced, as remanent radioactivity is minimal. The LEP population dose (defined as the total dose received by all persons associated with LEP) is at the most about 10% of the present annual CERN dose-commitment, or less that about 0.3 Sv/y ($\sim$ 30 rem/y). The population dose from LEP to all members of the public will be less than 3 mSv/y (300 mrem/y).

It is not obvious where, and by what means, dose commitments could be further reduced below the levels estimated in this report. One proposal would be to separate the experimental detectors from the adjacent experimental areas occupied by physicists by a complete shielding wall. This would reduce exposures in some limited areas and for some running conditions. The costs would be high because of increased construction costs, space, and longer cable runs to the detectors. However, the benefits would be minimal; the reduction in radiation dose would be at most of the order of 10 mSv/y ($<$ 1 rem/y) in each area for all staff working there.

In the klystron galleries the dose could be reduced by restrictions on personnel occupancy time. This measure will be reconsidered as soon as a radiation survey of the operating klystron area has been made and evaluated together with the need for personnel access. Because of the depth of the LEP tunnel, doses in the surface areas are completely insignificant and further optimization is irrelevant.

In general it can be stated that the LEP radiation protection system ensures that radiation doses and exposure to noxious gases satisfy all applicable legal requirements and are as low as reasonably achievable, taking all factors into account. In this way the personnel of LEP and those who live or work in the vicinity are assured of adequate radiation protection.

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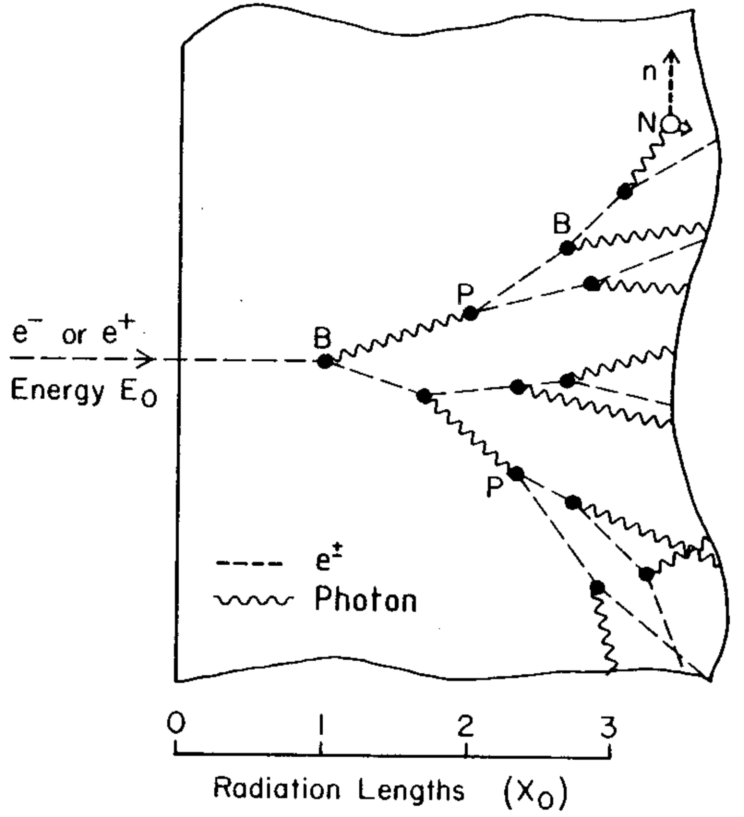


Fig. 1. Development of an electromagnetic shower produced by high-energy e$^{\pm}$. Electrons (e$^{\pm}$) and photons are represented by dashed and wavy lines, respectively.

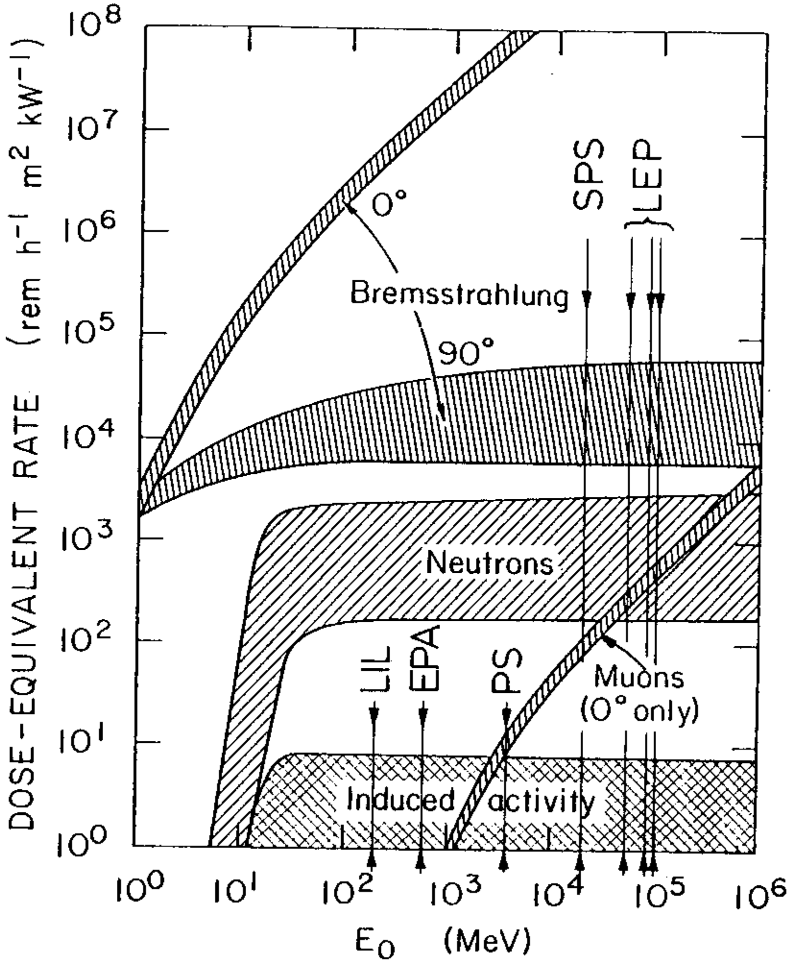
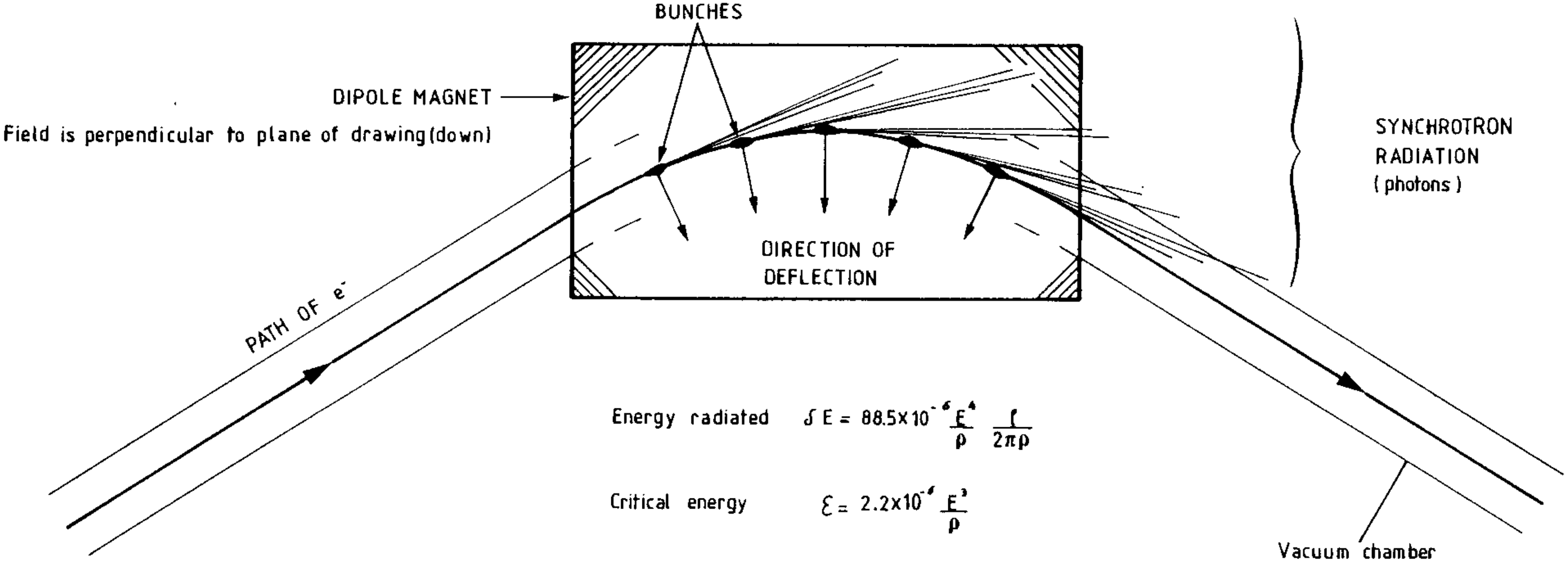


Fig. 2. Dose-equivalent rates per unit e$^{\pm}$ beam power expected if the LEP beam strikes a material of high Z and if no shielding is provided.



Energy radiated $\delta E = 88.5 \times 10^{-6} \frac{E^4}{\rho} \frac{\ell}{2\pi\rho}$

Critical energy $\mathcal{E} = 2.2 \times 10^{-6} \frac{E^3}{\rho}$

No of photons / m $\frac{dN}{d\ell} = 19.4 \frac{E}{\rho}$

$E, \mathcal{E}$, in GeV; ℓ, ρ, in metres

Fig. 3. Production of synchrotron radiation by $e^{\pm}$ beams deflected in a magnetic field.

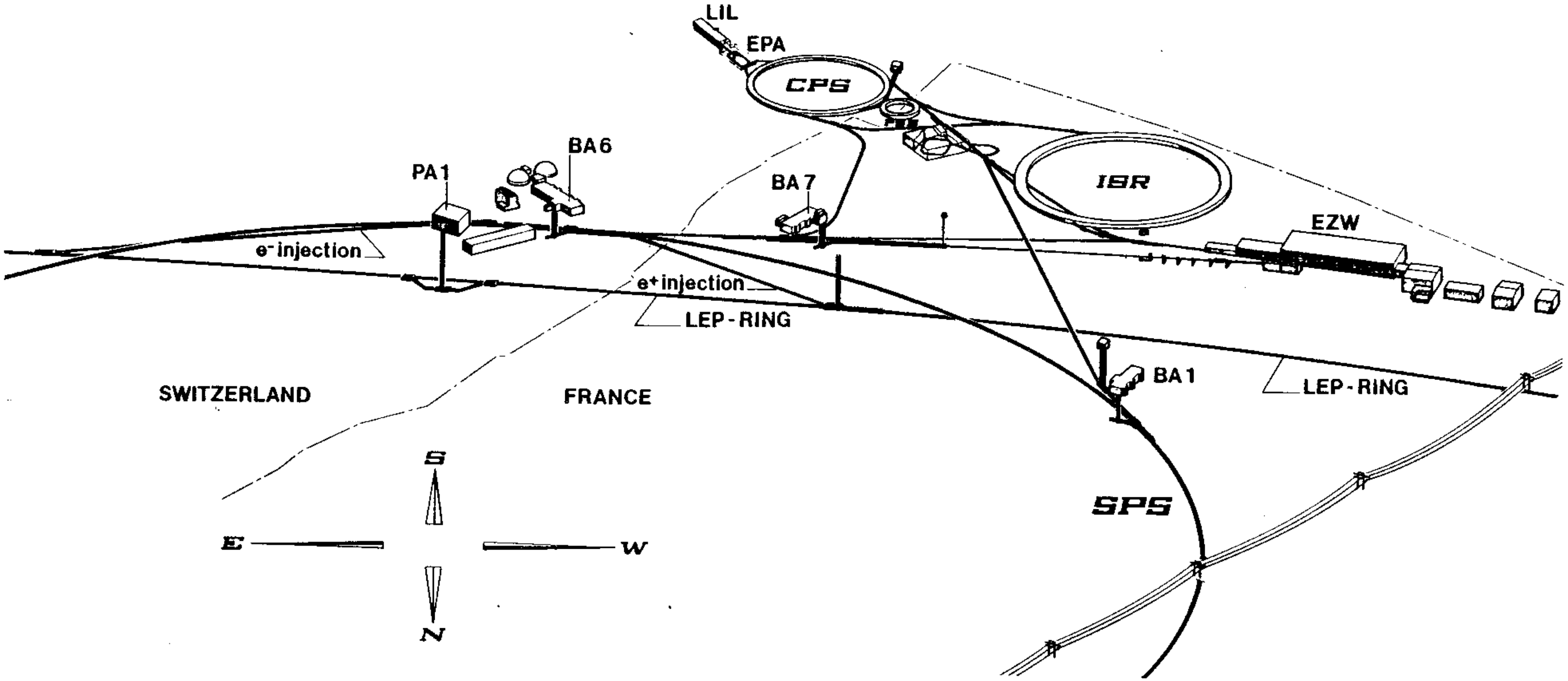


Fig. 4. Injection system for LEP.

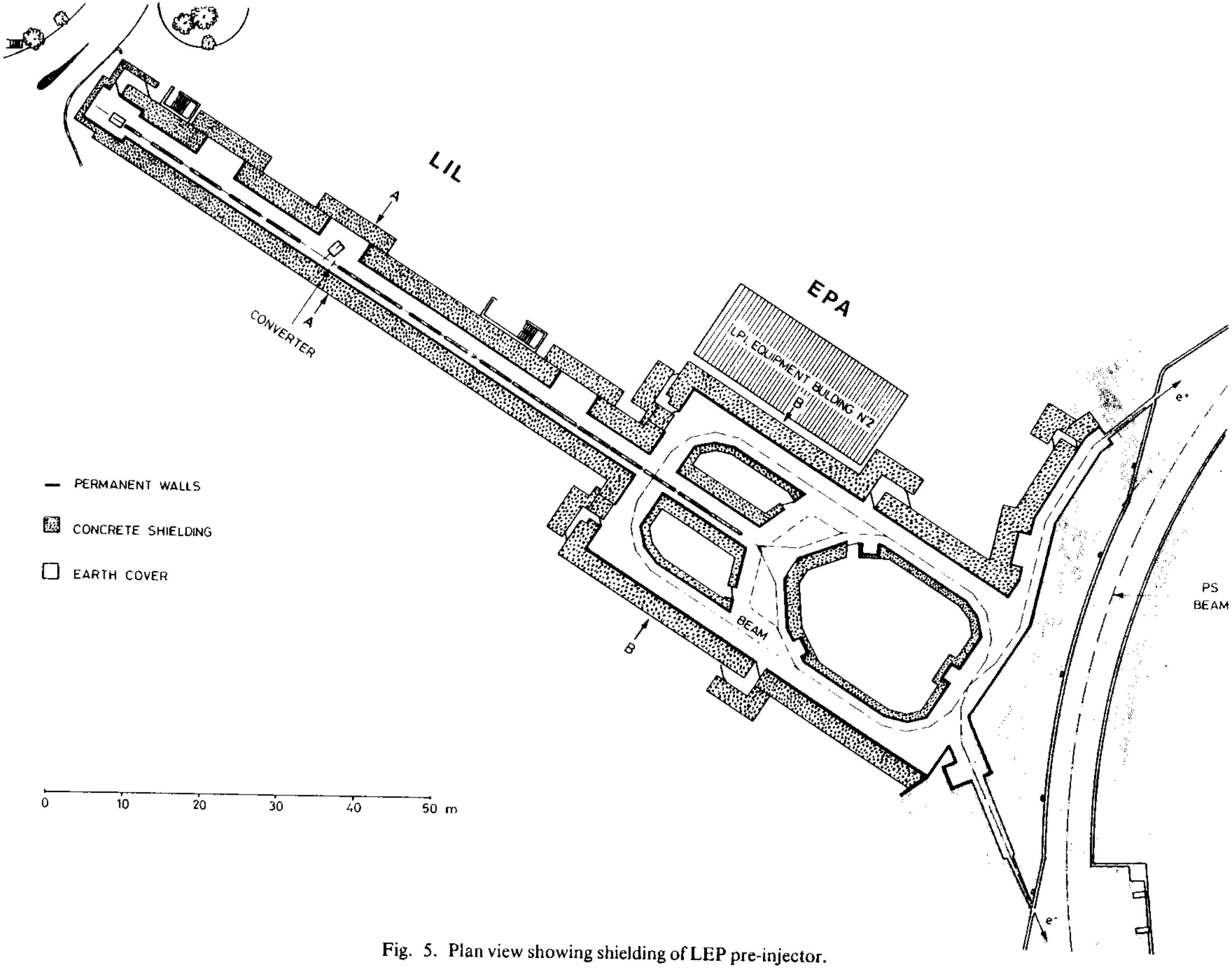


Fig. 5. Plan view showing shielding of LEP pre-injector.

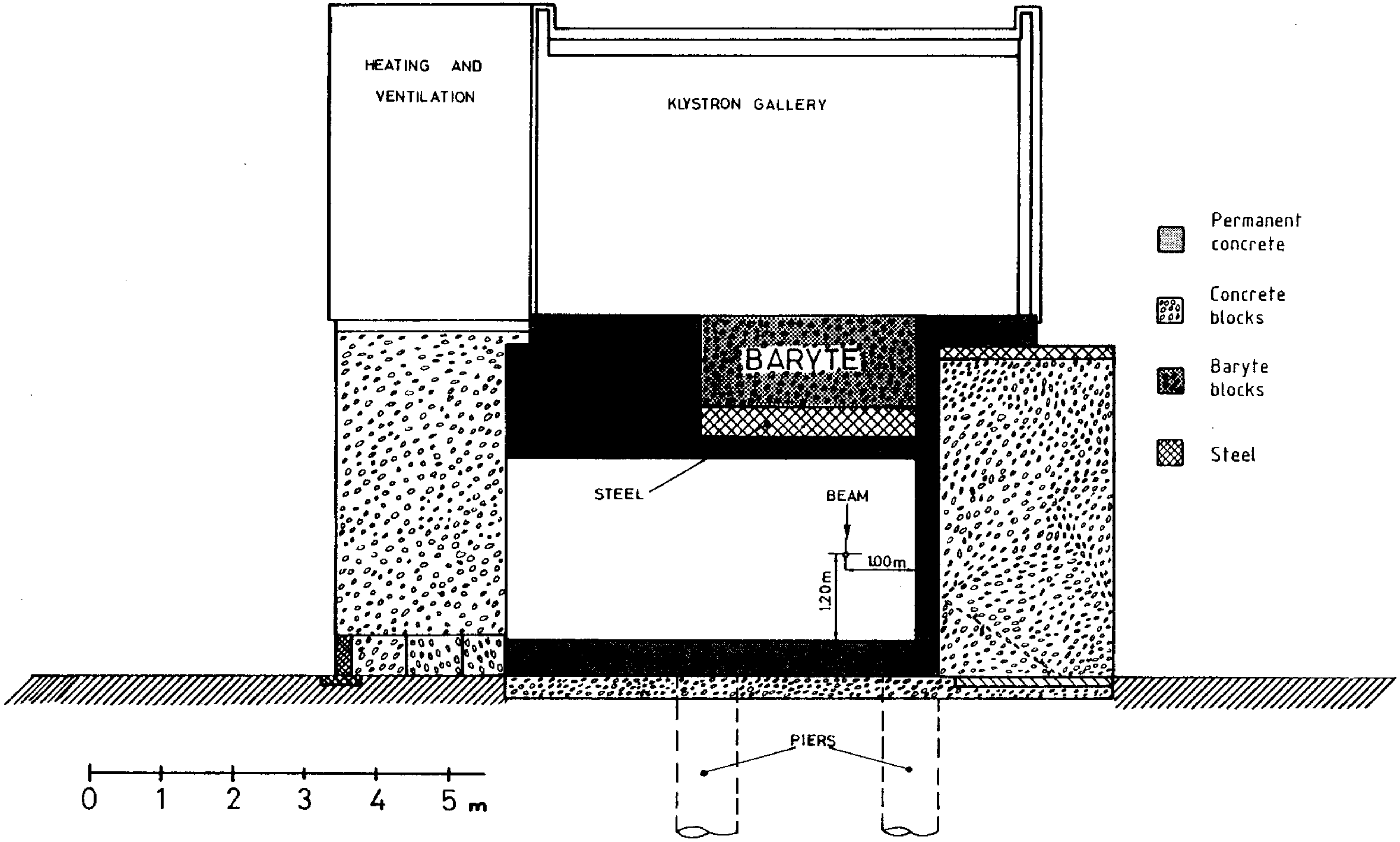


Fig. 6. Cross-section of the shielding around the Linear Injector for LEP (LIL) at the position of the converter (200 MeV e⁻ energy).

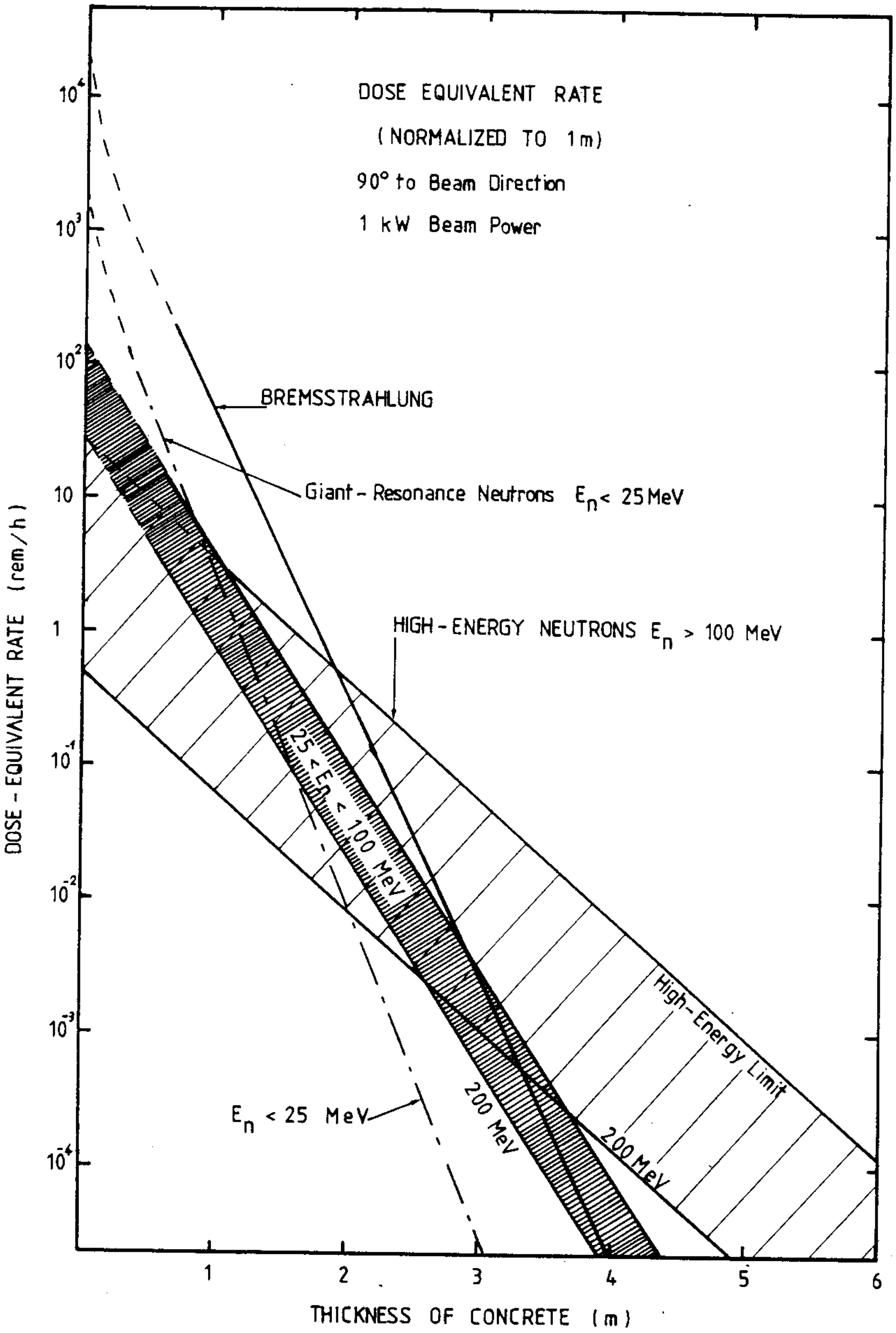


Fig. 7. Attenuation of radiation produced by e± beams as a function of concrete thickness.

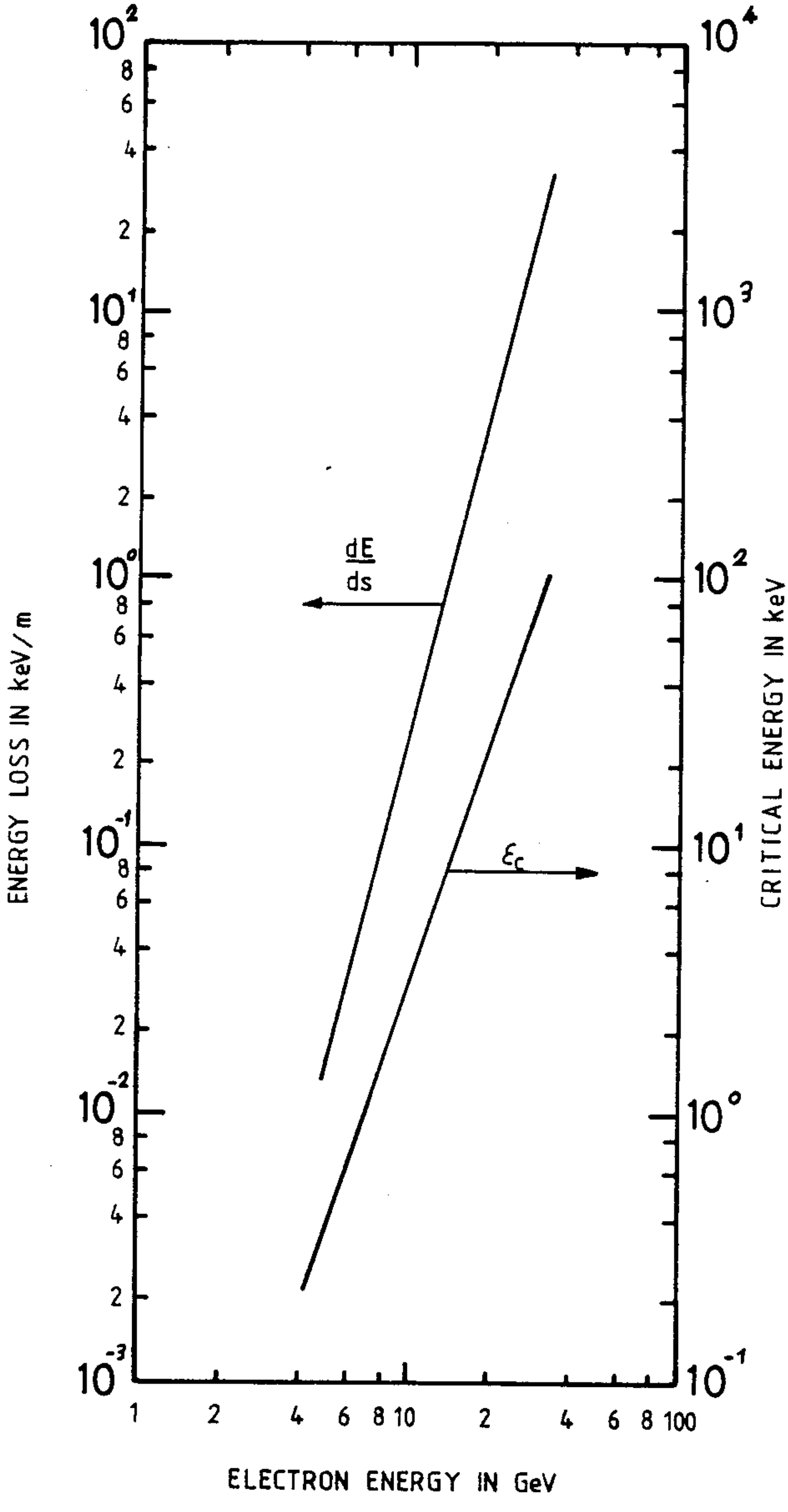


Fig. 8. Synchrotron radiation in the SPS (bending radius 741.3 m). Left-hand scale: energy loss per orbit path length as a function of particle energy. Right-hand scale: critical energy.

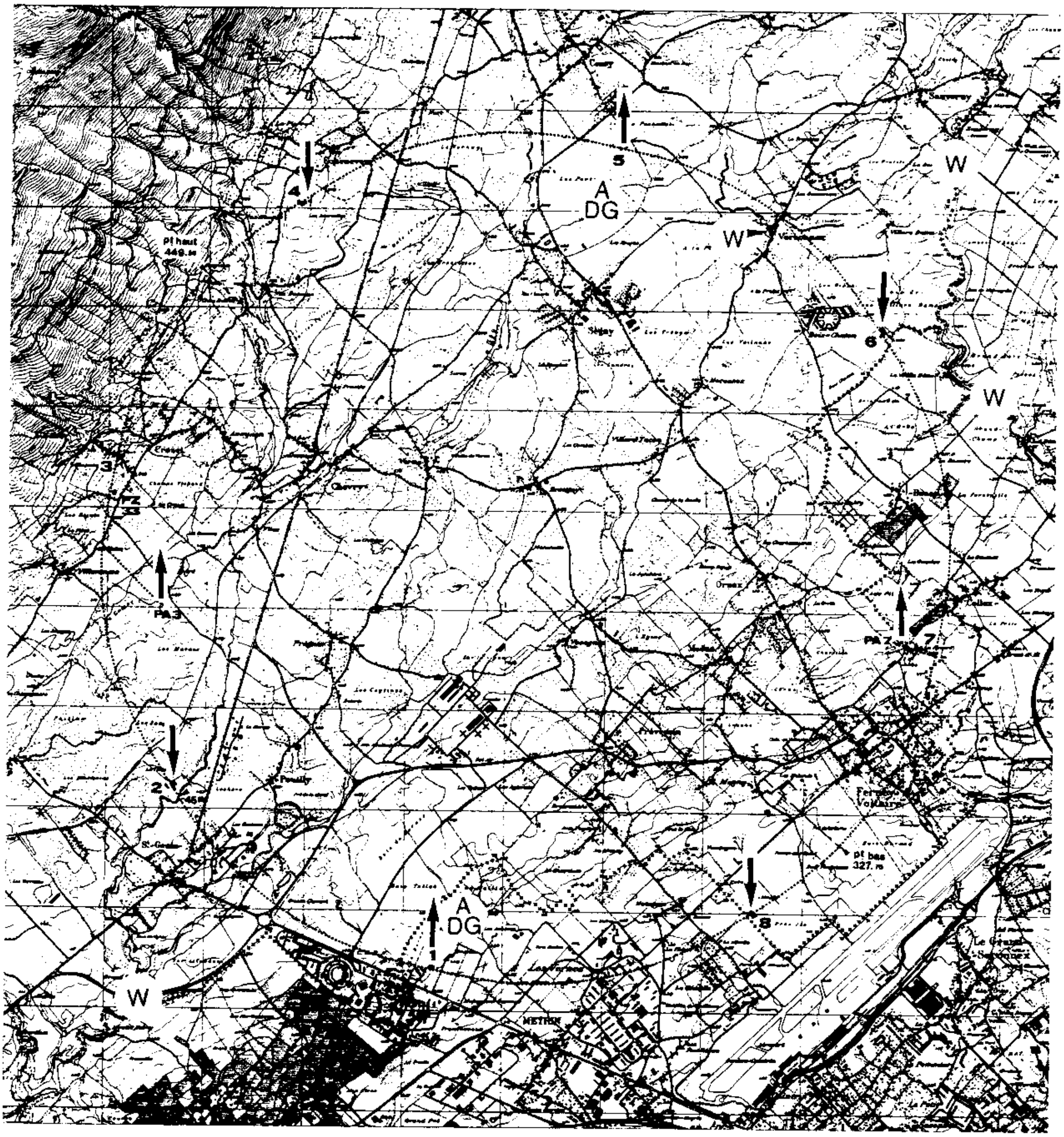


Fig. 9. The main LEP ring in its final position, and the locations for radiation and gas monitors and water sampling points. The ring area with the shallowest earth covering and the highest and lowest elevation of the main ring are also indicated: A: Monitor for activity in air; D: Monitor for ambient dose (gamma and neutron detector); G: Monitor for O_3 and NO_x concentration in air; W: Water-sampling point. Downward- and upward-pointing arrows: air intake and exhaust of the main-ring ventilation system, respectively.

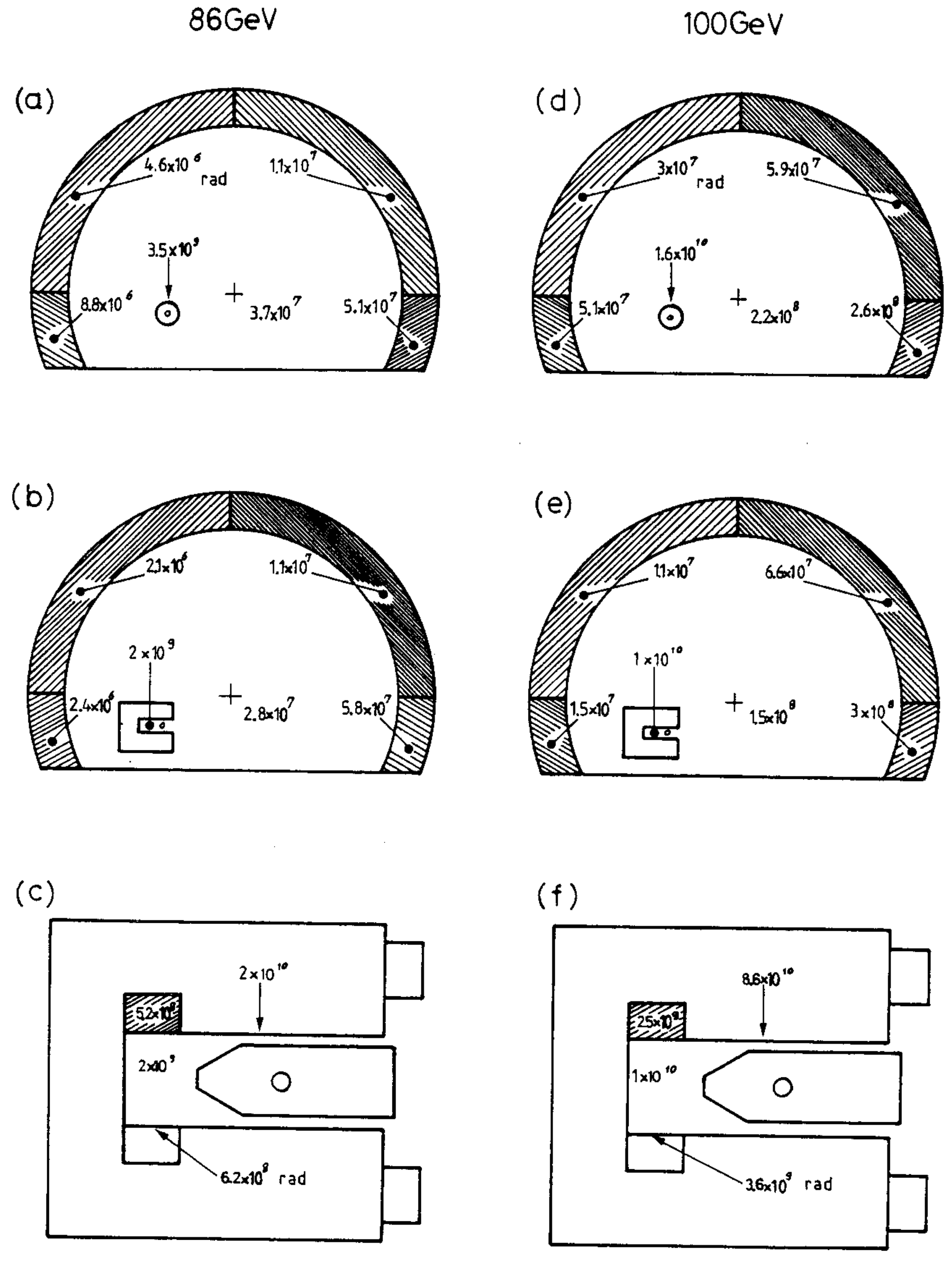


Fig. 10. Dose distributions produced by synchrotron radiation in the LEP tunnel during 10 years of operation (30000 h). Solid circles indicate averages within volumes shown; arrows indicate surface doses.

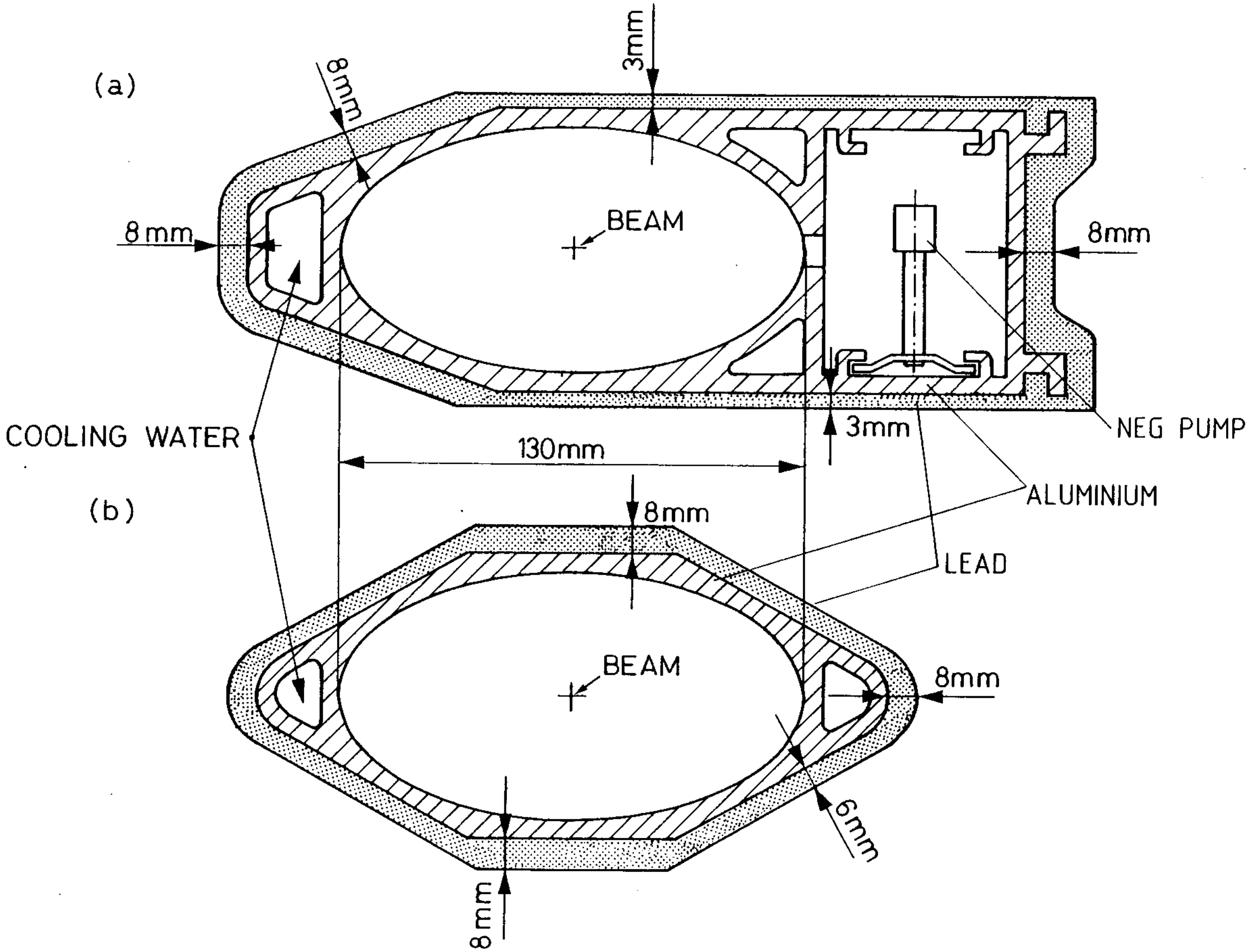


Fig. 11. Design of LEP vacuum chambers to be used in (a) dipole and (b) quadrupole magnets, showing lead shielding.

Fig. 12. Entrance to a radiation area.

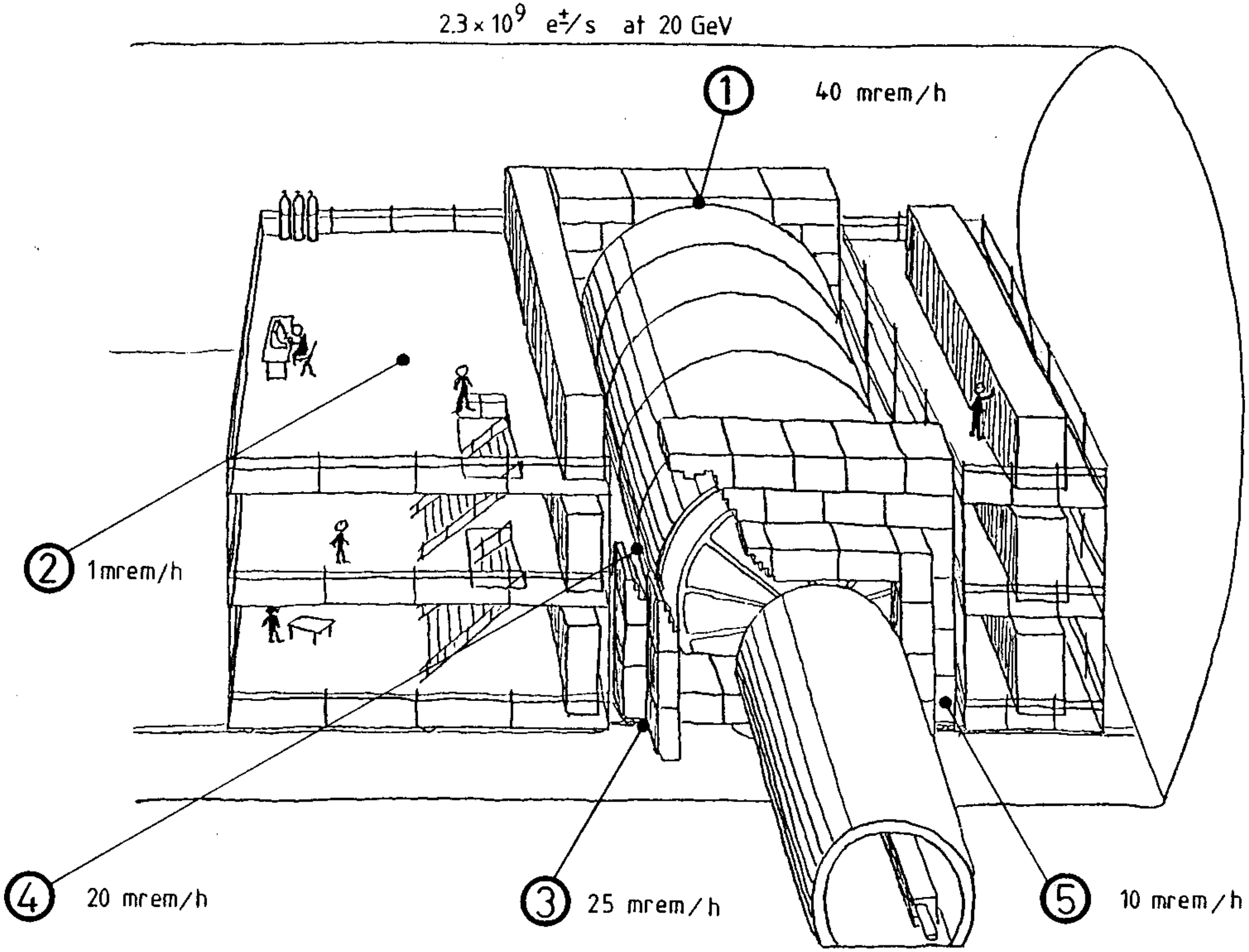


Fig. 13. Typical detector design and representative dose rates that could occur in occupied experimental areas.

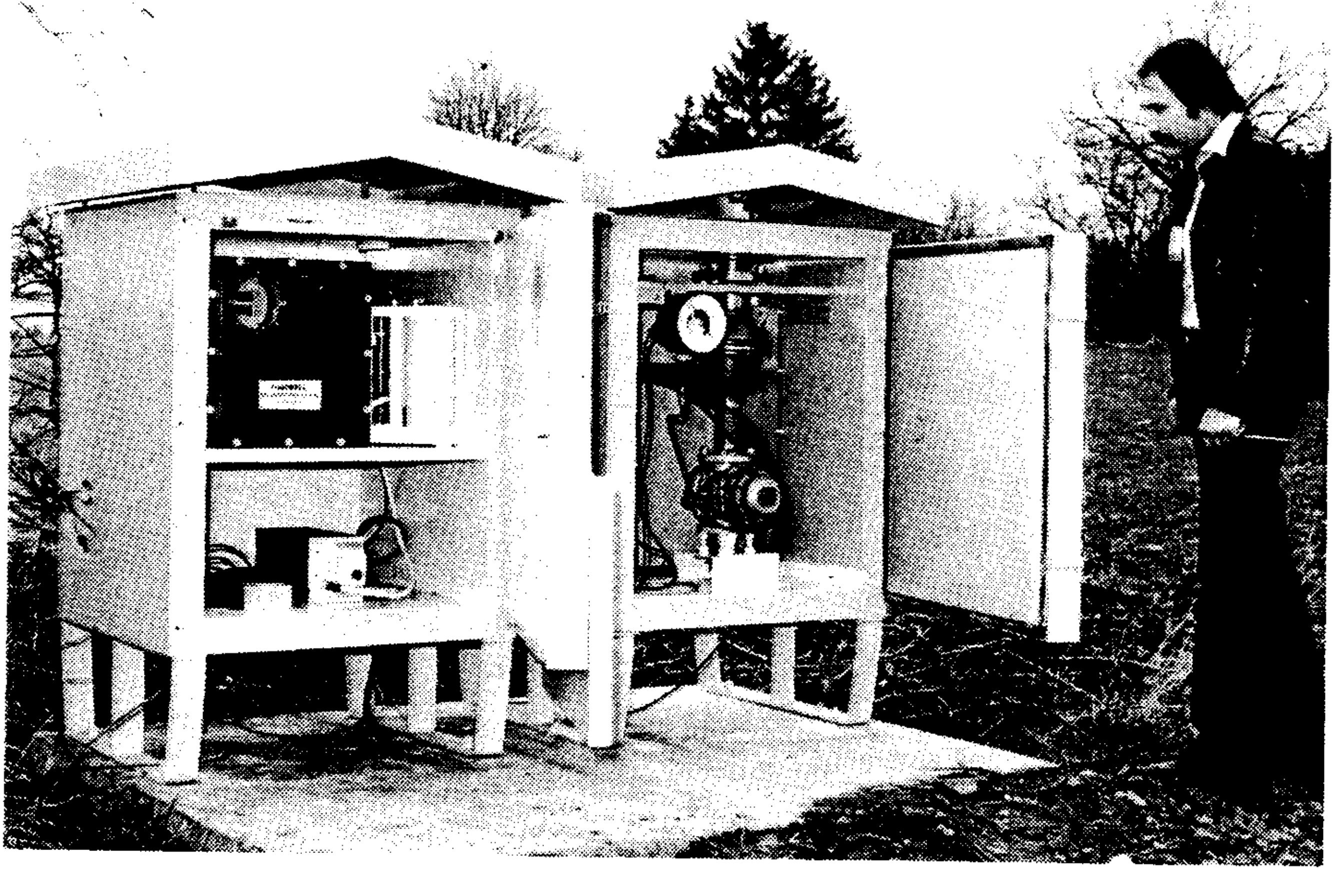


Fig. 14. Environmental monitoring station.

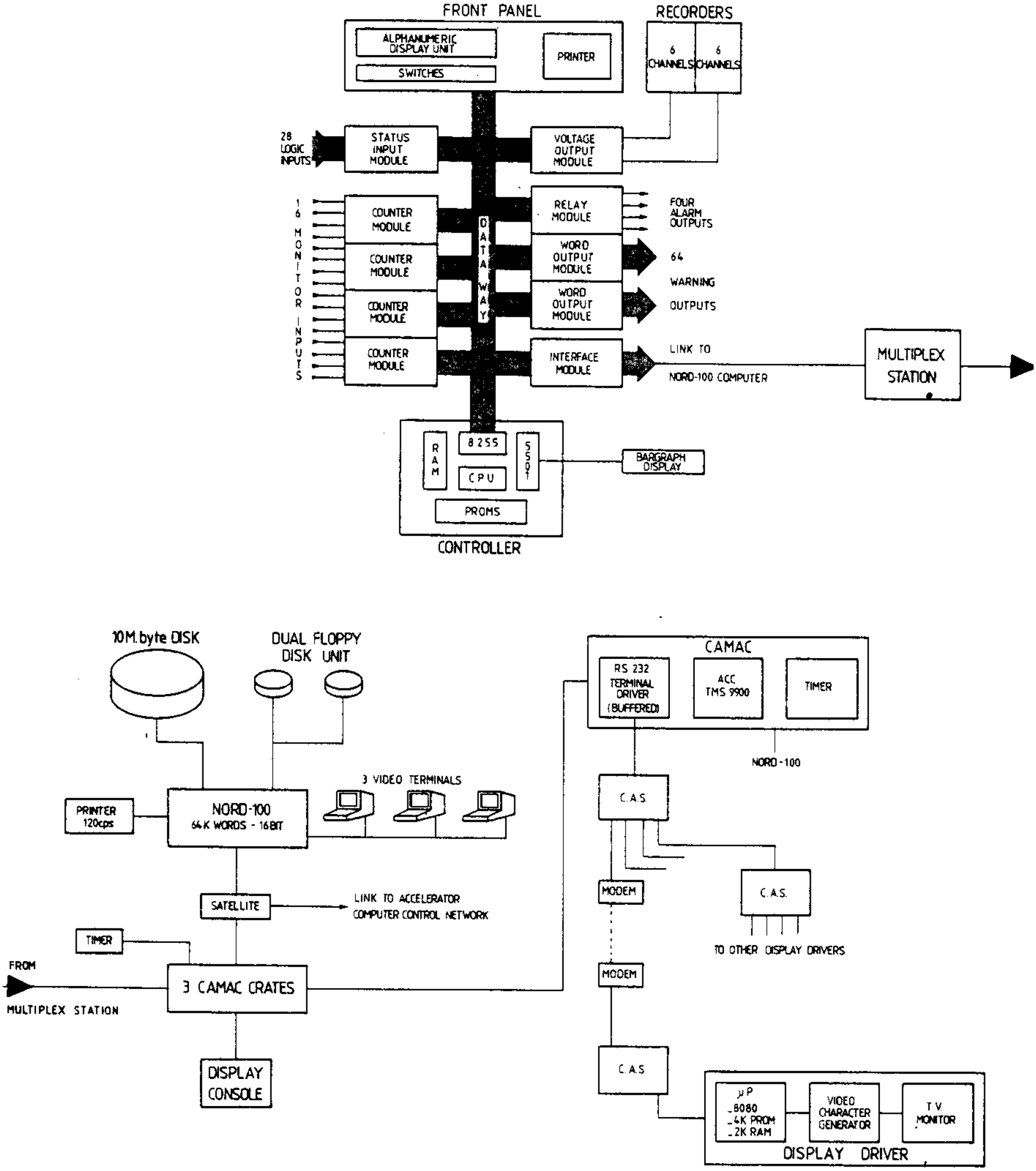


Fig. 15. Schematic of radiation monitor control and data-acquisition and handling system.