CERN 2006-007
24 July 2006

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Complex workplace radiation fields at European high-energy accelerators and thermonuclear fusion facilities

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GENEVA
2006

CERN–400 copies printed–July 2006

Abstract

This report outlines the research needs and research activities within Europe to develop new and improved methods and techniques for the characterization of complex radiation fields at workplaces around high-energy accelerators and the next generation of thermonuclear fusion facilities under the auspices of the COordinated Network for RAdiation Dosimetry (CONRAD) project funded by the European Commission.

Summary

The European Commission is funding within its 6th Framework Programme a three-year project (2005–2007) called CONRAD, COordinated Network for RAdiation Dosimetry. The organizational framework for this project is provided by the EUropean RAdiation DOSimetry Group EURADOS. One task within the CONRAD project was to provide this report which outlines research needs and research activities within Europe to develop new and improved methods and techniques for the characterization of complex radiation fields at workplaces around high-energy accelerators, but also at the next generation of thermonuclear fusion facilities. Starting from the beam parameters important to radiation monitoring (type, energy, intensity and time structure of the accelerated particles) one can make predictions of the composition of the radiation field outside the shielding and then decide the type of area monitors to be employed (active and/or passive) and how to calibrate them. This report first reviews the relevant techniques and instrumentation employed for monitoring neutron and photon fields around high-energy accelerators. Some emphasis is placed on some recent developments to improve the response of neutron measuring devices beyond 20 MeV. The influence of the pulsed structure of the beam on the instruments and the needs and problems arising for the calibration of devices for high-energy radiation are particularly critical issues which are also addressed. The major high-energy European accelerator facilities then are reviewed along with the way workplace monitoring is organized at each of them. The facilities taken into consideration are both research accelerators and hospital-based hadron therapy centres. The most relevant aspects of radiation field measurements at thermonuclear fusion facilities are addressed in one dedicated chapter. A chapter is devoted to describing on-going research in radiation dosimetry and development work in passive dosimetry and active counting and spectrometric instrumentation at several European national and international organizations. The final chapter discusses calibration problems and provides an overview of the neutron calibration facilities available in Europe.

Marco Silari, Editor

Contents

1 Introduction

Monitoring of ionizing radiation around high-energy particle accelerators is a difficult task due to the complexity of the radiation field. The capability to distinguish between the high-LET (mostly neutrons) and the low-LET components of the radiation field at workplaces, and to correctly measure them, is of primary importance to evaluate the exposure of personnel. At proton machines the dose equivalent outside a thick shield is mainly due to neutrons, with some contribution from photons and, to a minor extent, charged particles. At certain locations the radiation field may contain neutrons with energies exceeding tens of MeV, which contribute 30% to 50% of the ambient dose equivalent outside the shielding. At high-energy electron accelerators the dominant secondary radiations are high-energy neutrons, the shielding being thick enough to absorb most of the bremsstrahlung photons.

Similar high-LET and low-LET radiation components are present also at the nuclear fusion experimental facilities. The nuclear reactions used in these facilities, the deuterium-deuterium (D-D) and the deuterium-tritium (D-T), produce high flux of fast neutrons. The plasma current in the toroidal vessels (tokamak) of the fusion experiments based on magnetic confinement, the most practised fusion technology in Europe, generates bremsstrahlung X-rays. Special system components of some fusion facilities, like neutral beam injectors, have their own radiation environment due to neutron and photon fields. Neutron activation for D-T based systems, like JET, is elevated in the in-vessel components and sometimes it is important also in the material of some associated device and component, like in the water cooling system of the ITER project. The resulting radiation fields at workplaces, out of the concrete shielding that encase the main fusion facilities, are dominated by thermal neutrons but also fast neutrons and photons are present.

Neutron and photon dosimetry and spectrometry are thus essential tools in radiation protection dosimetry around both high-energy particle accelerators and nuclear fusion facilities. There are some similarities between these radiation fields and those encountered at flight altitudes. Several results shown later in this report come from measurements in aircraft and it is possible to partly "simulate" the radiation field in the atmosphere with accelerator-produced radiation. However, one important difference is that accelerators can operate in pulsed mode so that the radiation fields at workplaces can also be pulsed. This is an important aspect to be taken into account for instrument response; measurements of average dose equivalent rates for radiation protection purposes in these fields present a challenge for instrumentation.

Two types of dose quantities exist for radiological protection: body-related 'protection quantities' defined by the International Commission on Radiological Protection (ICRP) [(1)] and 'operational quantities' defined by the International Commission on Radiation Units and Measurements (ICRU) [(2)]. While protection quantities serve to define dose limits but are not directly measurable, the exposure can be monitored by calculations or by measuring the operational quantities. The protection quantity for the assessment of occupational exposures is the effective dose:

$$E = \sum_{\mathrm{T,R}} w_{\mathrm{T}} \cdot w_{\mathrm{R}} \cdot D_{\mathrm{T,R}}$$

where $D_{\mathrm{T,R}}$ is the mean absorbed dose deposited by radiation of type R in an organ or tissue T, and w_{R} and w_{T} are the corresponding weighting factors [(1)]. Calculations of protection quantities require comprehensive knowledge of the energy and directional distribution of the particles in the radiation field and of their interaction with tissue.

One operational dose quantity suited to demonstrate compliance with limits of the effective dose at workplaces is the ambient dose equivalent, $H^*(10)$, which is the dose equivalent, H, at a reference point at 10 mm depth in the ICRU sphere [(2)] under defined irradiation conditions. Many radiation protection instruments used to measure $H^*(10)$ follow measurement principles other than those used in the definition and therefore require calibration with respect to this quantity. An alternative and in general more accurate procedure is to measure the spectral neutron fluence and fold this information with an appropriate set of fluence to dose equivalent conversion coefficients. In practice monitoring instruments usually have a response function which approximately follows $H^*(10)$ for a given type of radiation and over a given energy range. The approaches to the determination of ambient dose equivalent for neutrons are discussed in detail in ICRU Report 66 (3). This report being restricted to spectrometry and area monitoring, the other important operational quantity, the personal dose equivalent, $H_p(10)$ is not discussed here.

Starting from the beam parameters of the accelerators important to radiation monitoring (type, energy, intensity and time structure of the accelerated particles) and from the characteristics of the radiation produced at the nuclear fusion facilities, one can make predictions of the composition of the radiation field outside the shielding and then decide the type of area monitors to be employed (active and/or passive) and how to calibrate them. This report reviews first (Section 2) the relevant techniques and instrumentation employed for monitoring neutron and photon fields around high-energy accelerators and fusion facilities, both in terms of dosimetry and spectrometry. Some emphasis is placed on some recent developments to improve the response of neutron measuring devices beyond 20 MeV. The influence of the pulsed structure of the beam on the instruments response is also addressed in Section 2. Section 3 reviews the major high-energy European accelerator facilities (with no presumption of being exhaustive) along with the way workplace monitoring is organized at each facility. The facilities taken into consideration are both research accelerators and hospital-based hadron therapy centres. The most relevant aspects of radiation field measurements at thermonuclear fusion facilities are addressed in Section 4. Radiation protection and monitoring at JET, the most important nuclear fusion plant operating nowadays in Europe, are considered and discussed. The radiation safety approach in the ITER design, the next technological step in the nuclear fusion development that will be hosted in France, is also presented. A few words are also spent in describing the experience acquired at a minor Italian nuclear fusion device. Section 5 discusses on-going research in radiation dosimetry and development work in passive dosimetry and active counting and spectrometric instrumentation at several European national and international organizations. Finally Section 6 discusses calibration problems and provides an overview of the neutron calibration facilities available in Europe.

2 Monitoring of mixed radiation fields

Stray radiation fields at high-energy particle accelerators are created by the intentional interaction of the accelerated beam with targets, beam dumps, collimators and by unintentional beam losses on structural components of the machine. At electron accelerators the secondary radiation is dominated by bremsstrahlung photons and high-energy electrons in the electromagnetic cascade. At high-energy proton accelerators beam interaction with material generates a hadronic cascade containing neutrons, charged hadrons, muons, photons and electrons with energy spectra extending over a wide energy range. An intense muon fluence may dominate in the forward direction with proton beams of energy exceeding about 10 GeV. The most common form of muon production is from the decay of pions and kaons. Above 10 GeV, muon shielding requirements dominate for high-intensity proton beams, meaning that a residual muon beam is often present behind a shield thick enough to attenuate the hadron component of the field in the forward direction.

This section describes the most important techniques used in the monitoring of mixed radiation fields, the response of the instruments to the various particles and examines the influence of the pulsed structure of the beam particles, and in turn the secondary radiation, on the instruments.

2.1 Neutron dosimetry and spectrometry

This section, which is partly based on a recent review of the subject [4], discusses the principal techniques employed for neutron monitoring at workplaces around high-energy particle accelerators: two are based on active instrumentation, moderator-type area monitors (rem counters) and Bonner spheres, and two employ passive dosimeters, bubble detectors and track etched detectors. This discussion is restricted to those methods which show a good response to high-energy neutrons.

2.1.1 Rem counters

The type of instrument employed for many years for neutron monitoring of neutron sources, at power stations and around particle accelerators is the so-called rem counter. A rem counter consists of a thermal neutron detector placed inside a moderator/attenuator designed in such a way that the response function of the instrument approximately follows the curve of the conversion coefficients from neutron fluence to $H^*(10)$ over a wide energy range. A commonly used instrument of this type is the Andersson–Braun (A–B) rem counter [5]. Its response is considered acceptable for neutron energies between thermal and approximately 10 MeV, although in reality the monitor underestimates $H^*(10)$ in the energy range from thermal to about 1 eV and above a few MeV, and overestimates it in the interval 1 eV to 100 keV.

The original design of the A–B rem counter dates back to 1963 [5]. The standard instrument consists of a thermal neutron detector enclosed within a moderator/attenuator assembly made up of an inner polyethylene moderator, a boron doped plastic attenuator and an outer polyethylene moderator. A number of holes are drilled in the plastic attenuator to allow part of the thermal neutrons to penetrate. Some recent commercial instruments have replaced the borated plastic by a cadmium layer. The thermal neutron detector is usually either a BF_3 or a ^3He proportional counter. The moderators employed in the different versions available have either a cylindrical, cylindrical with a rounded edge, or spherical shape, the latter ensuring a more isotropic response.

Regardless of the construction details, the drop in sensitivity restricts the upper energy limit to about 10 MeV. Above this value, the response falls sharply, leading to a drastic underestimation (about 40%) of the ambient dose equivalent, which increases with neutron energy. At the end of the 1980s, an extended range rem counter (named LINUS) was developed to overcome this limitation, which is particularly serious in a number of practical situations, e.g. around high-energy proton accelerators. The LINUS [6, 7, 8] was obtained starting from a commercial A-B monitor by inserting a 1 cm thick lead layer between the boron doped plastic attenuator and the outer polyethylene moderator. The effect of this additional material is an enhanced detection of neutrons with energy greater than about 10 MeV via low-energy neutrons produced in inelastic scattering reactions, neutrons that are subsequently moderated by the polyethylene and then detected by the BF_3 counter. Below 10 MeV, the response of the monitor is nearly the same as that of conventional moderator instruments.

Subsequently other instruments have been built based on the LINUS design (see, for example, refs. [9, 10, 11, 12]) and a number of improved models are now commercially available. These are for example model WENDI-II from Thermo Eberline, Erlangen, Germany, model NM500X from MAB GmbH, Munich, Germany and model LB 6411-Pb from Berthold Technologies GmbH, Bad Wildbad, Germany [13, 14]. Extensive tests of various commercial rem counters have recently been performed at GSI (Darmstadt, Germany) in high-energy neutron fields [15].The same concept of adding a lead liner has also been applied to Bonner sphere spectrometers (see Section 2.1.2).

2.1.2 Bonner sphere spectrometers

The need for spectrometry stems mainly from the fact that both area survey instruments and personal neutron dosimeters have a poor dose equivalent response as a function of energy. Spectra thus need to be known in order to determine precisely the dose equivalent values in fields where individuals are exposed to neutrons, e.g. in workplaces around accelerators, but also in the nuclear industry and at aircraft flight altitudes. Spectra also need to be determined to characterize calibration fields (see Section 6).

A multi-sphere spectrometer uses a thermal neutron detector at the centre of moderating spheres of different diameters, usually made of polyethylene. Fast neutrons are slowed down in the moderator and reach the detector as thermal ones, while the thermal neutrons initially present in the field are mostly captured in the moderator. Therefore the neutron energy, at which the sensitivity peaks, increases with sphere diameter. Due to the shape of the response functions, the energy resolution of the system is rather low but this can be judged as satisfactory for accuracy requirements in radiation protection and for the evaluation of the dosimetric quantities used in radiation protection.

Bramblett, Ewing and Bonner developed and tested the first multi-sphere detector in 1960, known widely since then as the Bonner Sphere Spectrometer (BSS) [(16)]. The first BSS consisted of a small cylindrical (4 mm high by 4 mm diameter) ^{6}LiI(Eu) scintillator optically coupled to a photo-multiplier placed at the centre of a series of polyethylene spheres. The size of the crystal was chosen to be small so as to allow good gamma-ray discrimination.

Later $^{10}BF_3$ proportional counters were used as an alternative to LiI crystals. BSS systems using small diameter cylindrical counters have been built and used extensively. Subsequently the use of ^{3}He proportional counters was investigated. The overall fluence responses of Bonner Spheres using a spherical Centronics ^{3}He proportional counter type SP9 are more than a factor of 10 higher than for the 4 mm by 4 mm LiI system. Additionally, the discrimination with respect to gamma rays and noise is excellent, except in the highest-intensity gamma ray fields where pile-up becomes a problem. The ^{3}He counters are fairly insensitive to radiations other than neutrons and their efficiency proved to be stable with time.

Passive detectors have also been used in Bonner spheres, in order to measure in intense pulsed neutron fields or in cases where a low-intensity neutron field requires a very long integration time such as in some environmental measurements. The types of passive detectors employed include activation detectors sensitive to thermal neutrons, pairs of ^{6}Li and ^{7}Li fluoride thermo-luminescent detectors, and track detectors with radiators made of ^{10}B, ^{6}Li or ^{235}U.

A sufficiently precise determination of the response functions can be obtained from Monte Carlo simulations supported by measurements with well characterized monoenergetic and isotopic source neutrons. Various unfolding codes employing different mathematical techniques have been developed to perform spectrum unfolding, such as MAXED [(17)] and GRAVEL [(18)].

In the past few years various groups have developed BSS with a response matrix extended to higher energies, following the same approach used in the development of the LINUS rem counter (see Section 2.1.1), i.e. by including a shell of high-Z material in the moderator (see, for example, Refs. [(19, 20, 21)]). As examples, the systems developed at PTB and at CERN in collaboration with the University of Milan are discussed in Sections 5.8 and 5.9, respectively. The NEMUS spectrometer of PTB and its response functions are shown in Fig. 1 and Fig. 2.

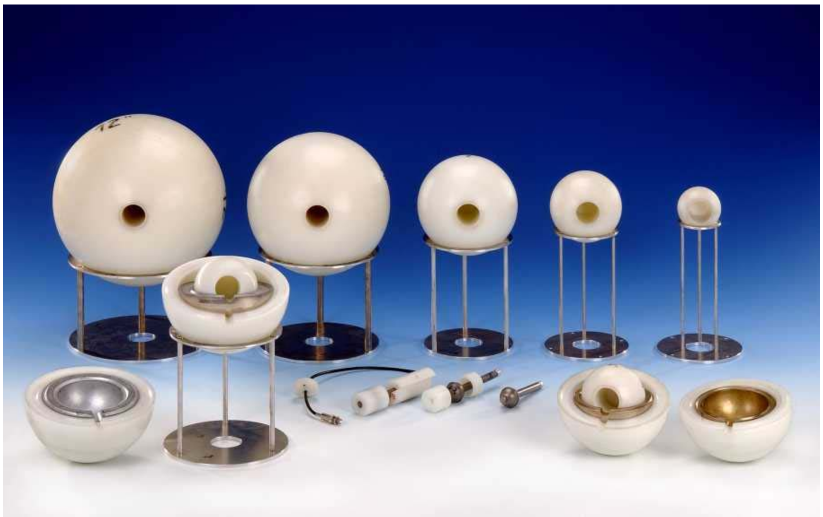

Fig. 1: In the back five of the ten polyethylene spheres (CH_2) of the PTB NEMUS spectrometer. In the centre, a spherical proportional counter (3.2 cm in diameter) filled with ^{3}He gas. In the foreground left and right, parts of the modified spheres. Both the polyethylene and the lead (left) or copper (right) shells are fabricated as half-shells. The combination of spherical shells of different thickness allows different sensitivities to be achieved.

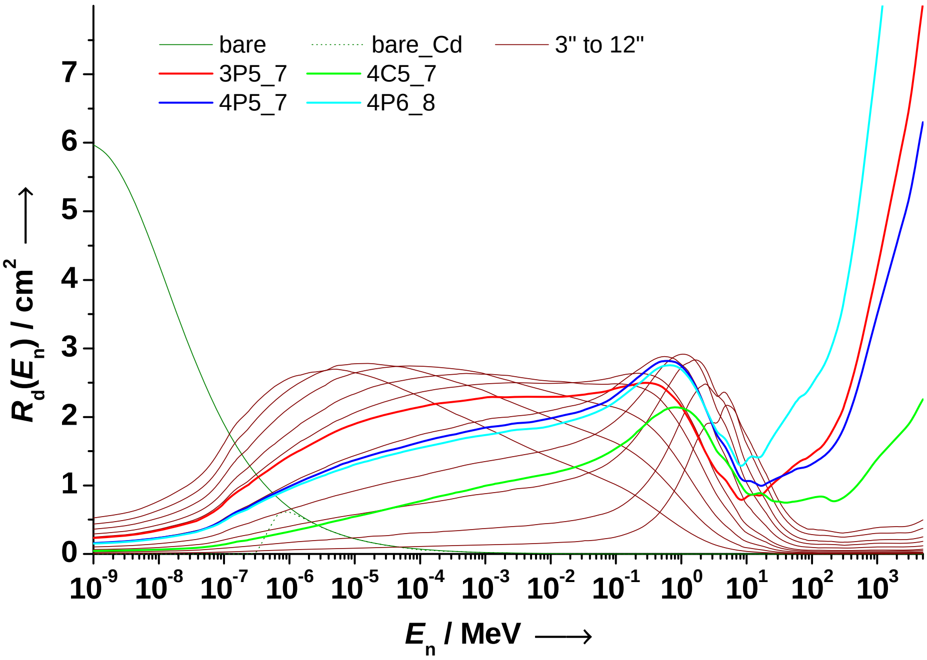

Fig 2: The response $R_d(E_n)$ of sphere d as a function of neutron energy E_n for the bare and cadmium shielded SP9counter (dark green), for the regular polyethylene spheres (brown) and for the modified spheres with embedded copper (green) and lead shells (cyan, red and blue) of NEMUS

2.1.3 Bubble detectors

'Superheated emulsion' is the name adopted by ISO and ICRU for detectors based on superheated droplets suspended in a gel, also known as bubble detectors or superheated drop detectors [(22)]. The suspended droplets consist of an over-expanded halocarbon and/or hydrocarbon which vaporises upon exposure to the high-LET recoils from neutron interactions. The superheated emulsion is contained in a vial and acts as a continuously sensitive, miniature bubble chamber (Fig. 3). The total number of bubbles evolved from the radiation-induced nucleation of drops gives an integrated measure of the total neutron exposure. Various techniques exist to record and count the bubbles forming in superheated emulsions. In passive bubble detectors, the most immediate read-out method is the visual inspection, a process that can be automated using video cameras and image analysis techniques. In active devices, bubbles may also be counted while they form by detecting the acoustic emission accompanying their explosive expansion. Further details on the physics and the operation of these detectors can be found refs. [22, 23, 24, 25].

Superheated emulsions are currently used either as personal and environmental dosimeters or as neutron spectrometers. Neutron spectrometry is performed by exploiting the different response to neutron energy against temperature or pressure of the superheated liquid. This section will only discuss the performance of these detectors as environmental dosimeters around high-energy accelerators, i.e. as devices capable of estimating the *H**(10). One of the advantages of passive bubble detectors is the possibility of determining an average ambient dose equivalent rate in a pulsed neutron field where active devices may suffer from dead-time losses or pulse pile-up. Another feature is that they are insensitive to low-LET radiation, X and γ rays as well as muons, which is a clear advantage when measuring the neutron component in mixed fields.

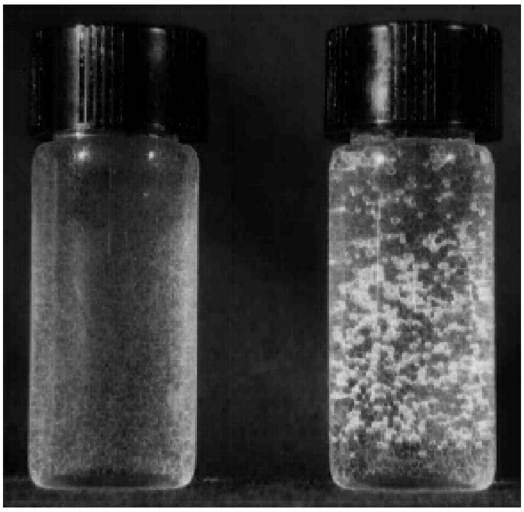

Fig. 3: Superheated emulsions (before and after irradiation)

The *H**(10) response is underestimated for epithermal neutrons (up to about 100 keV) and is fairly accurate in the neutron energy interval from 100 keV up to about 10 MeV [26]. The response to higher energies neutrons was measured by irradiating bubble detectors with quasi-monoenergetic fields in the energy interval 46-133 MeV. The results showed a significant underestimate of the *H**(10) [26]. The response was also calculated using the cross-section for charged particle production generated by the HADRON code [27], showing an agreement within 20% with the measured data. Measurements were also performed in the mixed field of high-energy radiation available at the CERF facility discussed in Section 6.4.1. An underestimation of about 40% with respect to the reference ambient dose equivalent was observed in that experiment.

Measurements in high-energy neutron fields generated by various types of hadron beams performed at CERN showed that bubble detectors underestimate the *H**(10) by a factor 0.4 – 0.7 depending on the neutron spectrum [28, 29]. The possibility of extending the response of bubble detectors to high-energy neutrons was investigated by exposing the dosimeters inside lead converters of various thicknesses [30]. Monte Carlo simulations showed that, as the thickness of the lead converter increases, a growing number of evaporation neutrons are generated by the high-energy component of the neutron field, thus enhancing the detector sensitivity, and this behaviour was confirmed experimentally. The comparison with the reference *H**(10) indicated that the required thickness of the lead converter is in the interval 1–1.5 cm. The response enhancement (about 25%) was confirmed [(26)] by exposing another set of bubble detectors inside a lead shell (1 cm thick) at CERF. The same detector/converter configuration led to an increase by a factor 1.3–1.4 in the response to 46–133 MeV quasi-monoenergetic neutrons [(26)]. The possibility of enhancing the response of superheated emulsions to high-energy neutrons was also investigated in a recent work [(31)]. A fairly flat response was observed by irradiating the dosimeter inside a lead converter (2 cm thick) with 40–75 MeV quasi-monoenergetic neutrons. Monte Carlo simulations were also performed to optimize the thickness of the lead converter. Finally at ESRF, where a network of 64 active bubble detectors [(32)] are installed around the 6 GeV electron storage ring (see Section 3.1.14.1) and interlocked to the accelerator personnel safety system [(33)] it was further verified that the addition of a 1 cm thick lead cylinder around the dosimeter increases the high-energy neutron response by almost 40% [(34)]. Therefore, a 1 cm lead shell has been added as a standard feature of the latest generation of acoustical bubble counters (Fig. 4) [(35)].

Fig. 4: Photograph of current acoustical bubble counters (open and with lead shell)

Investigations at ESRF also determined the response of the active bubble detectors to pulsed radiation and compared it with theoretical predictions [(33)]. The injected beam from the ESRF booster consists of 1 µs long pulses, with a repetition frequency of 1 or 10 Hz. In the case of a sudden stored beam trip, radiation is present during a few tens of µs, corresponding to the small number of turns the beam makes in the storage ring before being completely lost. Because of the relatively long duration of the acoustic pulse from bubble detectors (> 10 ms), a monitor will not be able to separately detect the creation of more than one bubble during a short µs-scale time interval. However, it can be assumed that the actual number of bubbles created per pulse, *n*, will follow a Poisson probability distribution, given by

$$p(n,\lambda) = \frac{e^{-\lambda} \cdot \lambda^n}{n!}$$

where λ is the theoretical number of bubbles per pulse, given by the ratio of the dose per pulse to the vial sensitivity (defined as the average dose needed to form one bubble). The typical sensitivity of the vials used at the ESRF is 100 nSv per bubble. The detection efficiency for pulsed radiation will then be given by

$$\frac{\sum_{n\geq 1} p(n,\lambda)}{\sum_{n\geq 1} n \times p(n,\lambda)}$$

The accuracy of the previous expression was verified by exposing the active bubble detectors to pulsed radiation with different values of dose per pulse, which were obtained by varying the peak current of the extracted beam [(33)].

2.1.4 Track etched detectors

Track etched detectors (TEDs) [36, 37] are based on the preferential dissolution of suitable, mostly insulator, materials along the damage 'trails' of charged particles of sufficiently high-energy deposition density. The detectors are effectively not sensitive to radiation which deposits the energy through the interactions of particles with low linear energy transfer (LET). In the complex radiation fields at high-energy accelerators and fusion facilities they can be used to characterize the neutron component.

Neutron detection and dosimetry by means of TEDs can be performed through the registration of fission fragments incident on a TED from an adjacent radiator [37, 38, 39]. In such cases inorganic TEDs (mica, glasses, minerals, etc.) can be used. Much more frequently, in particularly over the last few tens of years, polymer TED have been used which can register neutron induced lighter secondary charged particles, like protons, alpha-particles and other recoil nuclei. These secondary particles can originate from nuclear reactions both in materials adjacent to a TED and those created inside the bulk of it. The detection of lower energy neutrons by means of TEDs has been studied for more than 10 years particularly in connection with the cosmic radiation exposure of aircraft crew. Several possibilities have been studied:

- neutron dosimetry through the registration of light recoil nuclei mostly by means of electrochemical etching [39, 40, 41, 42],
- neutron dosimetry through the determination of the LET spectra in polyallyldiglycolcarbonate (PADC) TEDs [43, 44, 45],
- high-energy neutron detection through the registration of Bi-spallation fragments [41].

Their response characteristics are generally sufficiently well known for neutrons with energies up to several hundred MeV [46] (see for example Table 1 and Fig. 5). These dosimeters are generally able to determine neutron ambient dose equivalent down to a few tenths of a mSv.

Table 1: Energy dependence of neutron response of the HPA passive Survey meters [40, 46]

Radiation Field	**Net tracks[a] per fluence (cm^2 10^{-6})**	**Net tracks per ambient dose equivalent (mSv^{-1})**
144 keV (PTB)	2.25 (0.38)[b]	17.7 (3)[b]
542 keV (PTB)	14.1 (1.3)	42.0 (3.9)
1.13 MeV (PTB)	29.9 (2)	70.5 (4.7)
2.5 MeV (PTB)	41.3 (2.3)	99.4 (5.5)
5 MeV (PTB)	38.1 (1.7)	94.1 (4.2)
8 MeV (PTB)	34.8 (1.4)	85.1 (3.4)
14.8 MeV (PTB)	48.0 (2.3)	89.5 (4.3)
19 MeV (PTB)	54.7 (8.2)	93.6 (14)
60.2 MeV (UCL)	51 (5.5)	139 (15)
68 MeV (TSL)	42 (13)	121 (38)
95 MeV (TSL)	30 (9)	103 (33)
97 MeV (iThemba)	39 (4)	135 (19)
173 MeV (TSL)	20 (6)	80 (25)

a) Averaged over 3 orientations.

b) Total uncertainty.

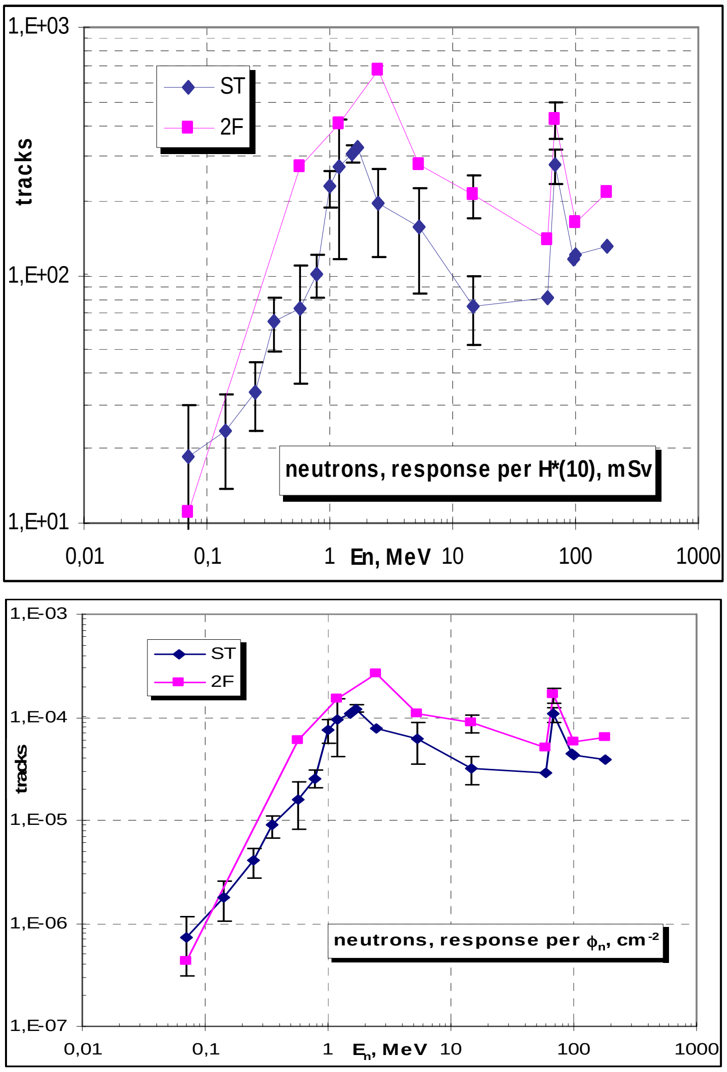

Fig. 5: Energy dependence of neutron response of the NPI ASCR electrochemically etched PADC [42, 46] (ST – combined chemical and electrochemical etching; 2F – two-frequency electrochemical etching)

2.2 Photon dosimetry and spectrometry

The most commonly used methods of gamma spectrometry with gamma-neutron discrimination in complex radiation fields is the use of NE213 or BC501A liquid scintillator cells coupled to a photomultiplier together with n-γ discriminator based on zero-crossing techniques (Z/C) [47, 48, 49]. The n-γ discrimination method is utilizing a difference in the intensity of the slow component of the light pulse in organic scintillators generated by recoil protons and electrons. The high-energy detection threshold depends of the size of the cell.

A complementary spectrometric technique for n-γ separation is the use of BGO semiconductor crystals. The detectors can be used up to a photon energy of 30 MeV.

Solid-state radiation dosimetry by electron paramagnetic resonance (EPR) spectroscopy and thermoluminescence (TL) are the two main passive techniques used for photon dosimetry in mixed radiation fields. Both are able to determine absorbed doses up to several thousands of Gy. However, while TLDs can measure doses from few μGy in some cases, the lowest threshold for EPR is several hundreds of mGy. The last method is therefore not suited for current radiation protection dosimetry.

2.2.1 Photon spectrometry

2.2.1.1 The BC501A liquid scintillator

The BC501A detector system shown in Fig. 6 allows measuring the energy distribution of neutrons and photons in the energy range from 1 MeV to about 100 MeV for neutrons and from 100 keV to 10 MeV for photons.

The scintillation liquid cell BC501A is well known for its ability to detect and discriminate fast neutron and photons [50]. Fast neutrons and photons create charged particles via elastic scattering and nuclear reactions and secondary electrons, respectively, with energy ranges between zero and the neutron incident energy or the Compton edge value for the photons. The secondary charged particles excite the scintillation molecules contained in the liquid. The decay of these molecules occurs through photon emission. Three decay modes associated to three decay times are known. The probability to excite each level depends on the nature of the secondary charged particle. The time characteristic of the scintillation light is then different for electrons and recoil protons, and therefore for photons and neutrons as shown in Fig. 7. This difference is used to discriminate the two types of radiation.

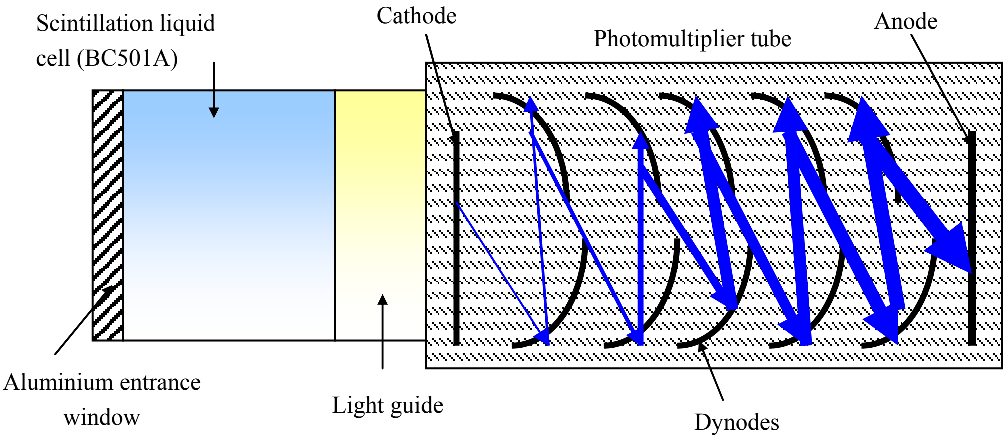

Fig 6: Scheme of the BC501A liquid scintillation system

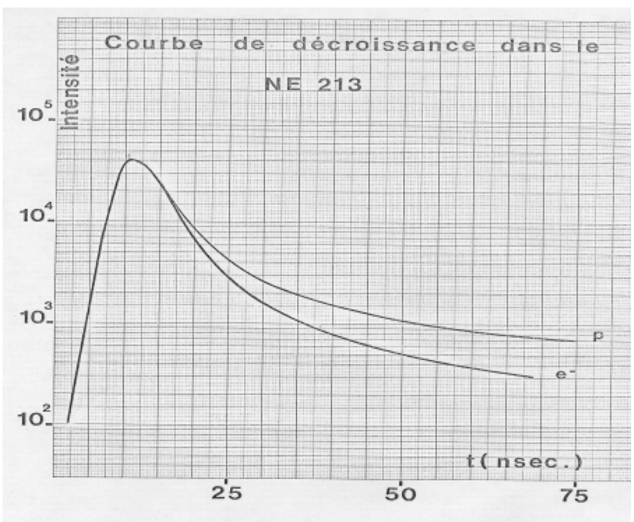

Fig. 7: Theoretical fall time of the anodic pulse for NE213 scintillator, used for n-gamma discrimination

The light produced by the scintillation mechanisms and transmitted by a light guide is transformed into an electron current by the photo-cathode of the phototube. A special gain stabilization unit, using a LED light to adjust the high voltage, can be applied to the phototube in order to avoid gain drift during the data acquisition. Two signals are used from the phototube: the first comes from the anode, the second from the ninth dynode. The fall time of the anodic signal depends on the nature of the secondary charged particle. The height of the dynode signal (after integration and amplification by a pre-amplifier) is related to the secondary charged particle energy. The discrimination between the pulses coming from recoil protons or heavier charged particles and Compton electrons is achieved by the use of the zero crossing method on the anode signal (with a pulse shape discriminator and a constant fraction discriminator). The information about pulse shape and pulse height are finally converted into digital information by an ADC and recorded in coincidence in a three dimensional plot by a computer creating the dual-parameter spectrum shown in Fig. 8.

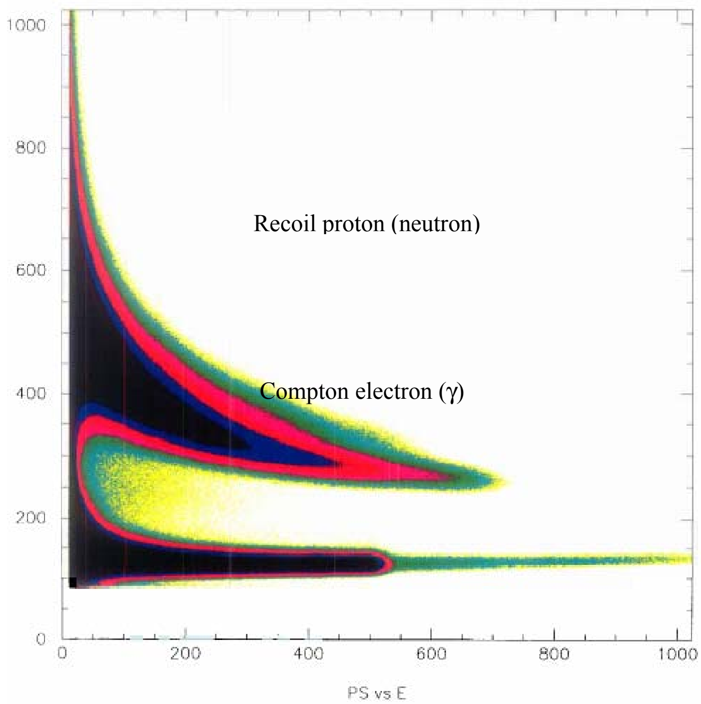

Fig. 8: Dual parameter spectrum giving number of counts as a function of the pulse height and of the pulse shape information

A data analysis process allows separating Compton electrons (produced by photons) and recoil protons (produced by neutrons). The separate projection of the two groups on the X-axis gives the energy distribution of the Compton electrons and of the recoil protons. The relation between the acquisition channel number and the Compton electron energy is linear. This is not the case for the recoil protons.

The energy resolution of the BC501A for the photon energies is rather weak since the detection signals are Compton edges (instead of photo-peaks as, e.g., with a germanium detector). Therefore the use of unfolding codes for the data analysis and spectrum determination is essential.

In mixed neutron/photon fields, one important point is the ability to discriminate the neutron-induced photons from the photons coming from the radiation field. Neutron-induced photons are mainly created via neutron reactions with the hydrogenous scintillation liquid. The response matrix of the detector for neutron induced photons for measurements in mixed fields must therefore be known.

2.2.1.2 BGO photon spectrometer

In the detection of high-energy γ-rays (E_γ > 3 MeV), the efficiency of semi-conductors (Ge) decreases rapidly with increasing E_γ. In this energy range scintillation crystals of bismuth germanate (BGO) or activated alkali-alidi NaI(Tl) are more suitable as efficient detectors of gamma radiation. BGO scintillators offer an attractive alternative to NaI(Tl) because of their larger (typically by a factor of 2.5) total gamma absorption coefficient. Moreover, compared to NaI(Tl), BGO exhibits a much superior gamma-ray-to-neutron detection ratio (51).

Bismuth Germanate (BGO) is a high *Z*, high density scintillation material with chemical composition $Bi_4Ge_3O_{12}$. Due to the bismuth high atomic number ($Z = 83$) and high density (7.13 g/cm^3), the BGO is a very efficient gamma-ray absorber, such that it can provide spectral coverage from about 150 keV to 30 MeV. An example of a spectrometer using a BGO crystal is shown in Fig. 9. The use of such a spectrometer in mixed neutron-photon radiation fields requires, like for the NE213/BC501A spectrometer, to take into account the response due to photons induced by neutrons in the detector.

Fig. 9: View of a BGO spectrometer (Harshaw, type NR: 4S4/1.5A – BX) coupled with a photomultiplier tube (Type HAMA 2060)

2.2.2 Geiger–Müller counters

Geiger–Müller (GM) counters are low cost devices, simple and easy to operate. Since they only count radiation induced events, any spectrometric information is lost. In general they are calibrated in terms of air kerma, for instance in a ^{60}Co field, and then the air kerma and dose equivalent can be measured. The response of GM counters to photons is constant within 15% for energies up to 2 MeV and shows considerable energy dependence above (52). The spectral fluence of the photons must therefore be known for the dose equivalent determination to be accurate.

The neutron sensitivity of GM counter tubes is described by the k_u value (53). The k_u values are used to correct the reading of the counter when used in a mixed neutron/photon field (54). The absolute spectral neutron fluence (or the relative spectral fluence and the neutron absorbed dose or kerma) must therefore be known to determine the number of neutron-induced counts, using the neutron fluence-to-kerma conversion coefficient for ICRU muscle tissue (55) and the energy dependent neutron sensitivity k_u coefficients. The neutron response of Geiger–Müller photon dosimeters was studied in details (54) for neutron energies between 100 keV and 19 MeV.

2.2.3 Passive photon dosimetry

2.2.3.1 Thermoluminescence dosimetry

One of the most common passive photon dosimetry techniques is based on the thermoluminescence (TL) mechanism. Thermoluminescent dosimeters (TLD) are inorganic crystals which exhibit a high concentration of trapping centres within the energy band gap. A radiation exposure of a TL material leads to the progressive build-up of trapped electrons and holes. After the exposure period, the temperature of the TLD sample, which is placed on a heated support or within a hot gas jet, is progressively raised. The recombination of liberated electrons and holes results in the emission of a photon. The total number of emitted photons or the light yield is within some limits proportional to the absorbed dose and hence it can be used for dosimetric purposes. TLDs are relative dosimeters and therefore they need a proper calibration, which is usually performed with ^{60}Co or ^{137}Cs photons.

TL dosimetry is widely used in many scientific fields, such as radiation protection, radiation therapy, space research, etc. The most commonly exploited is LiF:Mg,Ti (TLD100 or MTS), which is a nearly tissue equivalent material of good sensitivity and negligible fading at room temperature. It is also often applied for dosimetry of mixed neutron-gamma radiation, where pairs of ^{6}LiF and ^{7}LiF are normally used taking advantage of the difference in neutron cross-section of the two Li isotopes for thermal neutrons. Such pairs are typically used in moderators or Bonner spheres.

Except for these methods, several newer developments were introduced during the last decade in dosimetric practice and also began to find applications in the dosimetry of accelerator fields. First of all, one should mention the high-sensitive LiF:Mg,Cu,P detectors (TLD100H, MCP or GR200), which enable measurements of doses even below 1 µGy. Additionally their relative sensitivity to thermal neutrons is a few times lower that that of LiF:Mg,Ti (56), which makes ^{7}LiF:Mg,Cu,P a very good tool for measurements of gamma doses in mixed fields. Another new materials, Al_2O_3:C, which however is not tissue-equivalent, possesses similar properties (57). To improve neutron/photon discrimination of TLDs, ^{6}LiF detectors with very thin sensitive layer have been developed (58, 59).

In general the main advantages of the TLD technique are its high sensitivity, wide dynamic range and the extensive selection available of reusable dosimeters of various materials, sizes and shapes.

2.2.3.2 EPR dosimetry

Solid-state dosimetry by electron paramagnetic resonance (EPR) spectroscopy consists in the measurement of the concentration of free radicals induced by ionising radiation in irradiated materials (60). This technique, which has proven useful for a variety of applications especially for high doses, is particularly helpful for individual dose reconstruction after radiological accidents. EPR dosimetry allows, when using two materials with two different responses to neutron and photon (for example alanine pellets and sugars) to estimate the two dose components of a mixed neutron-photon field over a wide dose range (0.5 to 50×10^3 Gy). To use these dosimeters in mixed fields, it is necessary to estimate their response to other types of radiation. It is worth noting that EPR dosimeters are considered as tissue equivalent for photon and neutron over a wide energy range.

2.3 Detectors based on microdosimetric principles

Active dosimeters (TEPC counters and recombination chambers) are based on microdosimetric principles. They allow the measurement of the total dose equivalent and to discriminate the low- and high-LET components of the radiation field. This principle seems to be especially useful for complex, high-energy fields, when the concept of gamma-neutron separation is not sufficient because other radiation components, e.g. muons, may also contribute to ambient dose equivalent. There is practically no upper energy limit for these detectors, if specially designed devices and measuring methods are employed.

2.3.1 Tissue-equivalent proportional counters

Tissue-equivalent proportional counters (TEPC) are detectors capable of measuring the probability distribution of absorbed dose *d(y)* in terms of lineal energy *y*. The lineal energy is a stochastic quantity defined as the ratio of the energy imparted to the matter in a volume by a single-deposition event to the mean chord length in that volume [(61)]. TEPCs are proportional counters containing a tissue-equivalent (TE) gas inside a TE plastic cavity chamber. Acting on the gas pressure, it is possible to simulate the energy deposition events in microscopic volumes. The distributions of the microdosimetric quantities measured with TEPCs are applied in radiation biology, radiation chemistry, radiation protection, radiation therapy and dosimetry [(61)]. This section only discusses the use of these microdosimeters for ambient monitoring. From the probability distribution of absorbed dose *d(y)* one can evaluate the dose equivalent through a function *Q(y)* [(62)] which relates the quality factor to the lineal energy because *y* can be used as an approximation of the linear energy transfer, LET.

The energy deposition in the TE gas is measured through ionization of charged particles composing the primary radiation field and/or of secondary particles generated mainly in the walls of the detector. One of the main features of TEPCs is their capability of measuring the dose equivalent in a mixed radiation field using only one detector independently of the type and energy of radiation.

An example of this type of instrument is the HANDI-TEPC in use at CERN. This dosimeter [(63, 64)] is based on a spherical TEPC with a wall thickness of 0.15 g cm^{-2} filled with a propane-based TE gas and simulates a tissue sphere 2 mm in diameter. The absorbed dose spectrum is divided into 16 approximately equidistant channels on a logarithmic scale from y = 50 eV μm^{-1} up to 1.5 MeV μm^{-1}.

As an example of application of this type of instrument at high-energy accelerators, the HANDI was employed to measure the probability distribution of absorbed dose in the stray radiation field produced by lead ion beams at CERN [(65)]. The *d(y)* spectrum is characterized by a marked low-LET component (50 eV $\mu m^{-1} \leq y \leq$ 6.12 keV μm^{-1}) which is mainly due to muons, whilst the high-LET component is mainly due to neutrons. The total dose equivalent reading was slightly higher than that measured with the LINUS area monitor (see Section 2.1.1) in all locations except for one case where the dose equivalent evaluated with the HANDI was found to be higher by a factor of 1.6-2.4 than that evaluated with four different LINUS survey-meters. These differences were ascribed to the fact the high-LET component of the microdosimetric spectrum may contain contributions other than neutrons. The presence of charged particles in the radiation field at the location with the higher discrepancy was signalled by a ^{11}C scintillator activation detector (which, above about 20 MeV, detects charged hadrons as well as neutrons), while the neutron spectrum assessed with a set of Bonner spheres showed very few neutrons above about 10 MeV.

The use of TEPCs around high-energy accelerators may be hindered by loss of counts due to dead time, the saturation of the ADC channels and pulse pile-up [(64)]. The HANDI showed count losses against the dose equivalent rate from various gamma and neutron isotopic sources [(64)]. These losses were found to be more pronounced in the low *y* channels. Negligible losses were observed in the mixed pulsed radiation field at CERF (see Section 6.4.1 and Fig. 10) up to dose equivalent rates of about 5 mSv/h. The CERF radiation field consists of radiation pulses lasting 2.5 to 5 s repeated every 15 s. Measurements were also performed in a strongly pulsed stray field produced by beam losses at the ejection of the CERN proton synchrotron (PS) [(66)]. The microdosimetric spectra resulted to be distorted by pile-up effects. In particular, a pronounced pile-up peak was observed above y = 100 keV μm^{-1}, thus emphasising the limit of applicability of this active detector in strongly pulsed fields.

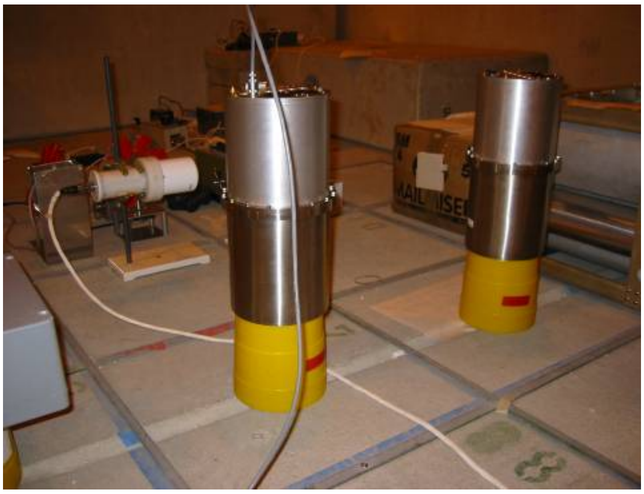

Fig. 10: Measurements with TEPC at CERF

2.3.2 Recombination chambers

Recombination chambers, i.e. high-pressure ionization chambers involving the initial recombination of ions, are usually considered as detectors of the total ambient dose equivalent $H^*(10)$, or, separately, the ambient absorbed dose, $D^*(10)$ and average quality factor, Q^*, of a mixed radiation field. Some recombination methods make it possible also to separate the photon component (or, in a broader sense, the low-LET component). Such methods are the recombination microdosimetric method (RMM), its simplified version, called the two-component RMM [(67)] and the extrapolation recombination method (ERM) [(68)]. These methods require applying several voltage values to the electrodes of the recombination chamber.

Another type of recombination chamber can be applied for photon dosimetry in mixed photons/neutrons fields using the two-detector technique. This is a high-pressure, hydrogen-free chamber, usually with graphite or aluminium electrodes and filled with carbon dioxide up to about 3 MPa. The chamber is operating at low polarizing voltage, in conditions of strong initial recombination of ions in high-LET particles tracks. The neutron-to-photon sensitivity ratio of the chamber is strongly reduced by the initial recombination of ions created in the tracks of alpha particles and nuclear recoils generated by neutrons. The photon kerma can be determined separately, using this method, if the energy of accompanying neutrons does not exceed some tens of MeV [(69)]. At higher energies, the low-LET component is more meaningful than the photon component, and can be determined using other recombination methods, e.g. RMM, in mixed radiation fields of any composition and unlimited energy range.

2.4 Pulsed fields and instrument response

Most accelerator facilities, such as linear accelerators, synchrotrons or field emission impulse generators operate in pulsed mode. Usually such sources deliver their output pulses within the range from nanoseconds to tens of microseconds spaced by at least a few milliseconds. This also concerns most of conventional electron linacs used in radiotherapy, which are operated at repetition rates varying from 100 to 400 pulses per second with pulse widths of about 1 to 10 µs. In some accelerators the microsecond output pulses consist of a series of separate ‘bunches’ each of duration of a few picoseconds, while the interval between bunches is generally less than one nanosecond. This time structure within the microsecond pulse can usually be ignored for radiation field spectrometry and dosimetry.

Radiation protection at workplaces deals with stray radiation fields outside shielding. In the most complex cases at high-energy accelerators, such radiation fields comprises neutrons, photons and charged particles, with pulses which are usually shorter than 10 μs with high instantaneous fluence rates and dose rates. Measurements of average dose equivalent (rate) for radiation protection purpose in these fields present a challenge for instrumentation and may become even more difficult at workplaces in the vicinity of new facilities with increasing particle energy.

At present, the time structure of the stray radiation fields is usually deduced from the design of the accelerator. Little or no experimental work has yet been reported in the open literature concerning the pulsed structure of the radiation field modified by transport through the shield. It can be expected that thick shields of high-energy accelerators may seriously disturb the initial pulse structure because of e.g. different time of flight of secondary particles through the material of the shield. The information about the real time structure behind the shields can be important in order to decide whether a particular radiation field must be considered to be pulsed, for a particular dosimeter. An important problem can also be represented by the time structure of high-energy neutron leakage from spallation targets.

The influence of pulsed radiation on the response of radiation detectors is considered in the literature first of all for dosimetry of the primary beam. The guidelines from such studies can be applied in radiation protection at workplaces but lower dose rates at workplaces comparing to the beam conditions should be taken into account.

The most comprehensive source of information on the dosimetry of pulsed X-ray or electron beams is the ICRU Report 34 (70). The measurements using ionization chambers, chemical dosimeters, calorimeters and solid state devices are discussed. The report provides information on certain precautions and the selection of calibration constants needed for dosimetry of pulsed low-LET radiation.

High-LET radiation, mainly heavy charged particles or neutrons, is only shortly mentioned in the ICRU 34, because there was not enough information about the influence of radiation pulsing on dosimetry in complex radiation fields, at the time when the report was issued (1982).

Some up-to-date information and operational guidelines for radiation protection at particle accelerator facilities with energies from about 5 MeV up to the highest energies available can be found in NCRP Report No 144 (71). Section 5 of this report addresses also the special problems of measurements in pulsed radiation fields.

Workplace monitoring in complex radiation fields usually involves instruments based on the use of ionization chambers, particle counting devices or solid state detectors. The last two types of detectors are also often used in neutron and charge particle spectrometers. Tissue equivalent proportional counters (TEPC) and recombination ionization chambers are used for microdosimetry and LET-spectrometry. The influence of the pulsed structure of the particle beam on the instrument response is different for the three classes of detectors.

2.4.1 Ionization chambers

The pulsed structure of the radiation fields may influence first of all the ion recombination correction. Very often the recombination correction is obtained experimentally by extrapolating the inverse of the chamber reading R as a function of the inverse of the polarizing voltage U to $1/U = 0$. Such approach is correct for small chambers used in pulsed X-ray or electron beams, e.g. at irradiation conditions typical of those encountered in radiotherapy, with dose rates of about 0.05 mGy to 1 mGy per pulse. The ion recombination in commercial cable-connected ionization chambers may then amount to about 1% or slightly more and the extrapolation method corrects for both initial and volume recombination and for charge loss by diffusion.

The situation is much different for large ionization chambers, used for radiation protection at workplaces. The ion-collection time in such chambers may be long compared with the period between pulses and the chamber will then behave as if subjected to continuous rather than pulsed radiation. In such case, the corrections for volume recombination are based on a linear dependence of *1/R* on $1/U^2$. This approach neglects initial recombination and diffusion, however for dose rates typical for workplaces the situation is opposite — volume recombination can be neglected but initial recombination should not. Therefore, the correction for initial recombination must be applied first, before the correction for the volume recombination, if needed.

In the ionization chambers for dosimetry of mixed radiation fields, special gases or gas mixtures with saturation characteristics different from those of air are often used. If a gas is used in which negative ions are formed, initial recombination in the tracks of recoil protons will be greater than in electron tracks. This fact has to be taken into account in the determination of the initial recombination correction, which may considerably differ from the simple linear dependence of *1/R* on *1/U*. In many cases, the experimental determination of the correction factor from the measurements of the ionization current in the considered radiation field, but at different dose rates, may provide the best accuracy.

2.4.2 Solid-state dosimeters

Solid-state dosimeters are based on a wide range of radiation effects including the change of optical absorption in glass and plastic materials after irradiation, the effects in thermoluminescent and photoluminescent materials, and semiconductor detectors (for personal dosimetry). Generally, there is no information about special problems of measuring pulsed radiation with such detectors, except semiconductors which may react on radiofrequency electromagnetic fields. For other solid state detectors it can be expected that the effect of the radiation pulsing should be rather a second order correction for the dose rates encountered at workplaces.

2.4.3 Particle-counting devices

Pulsed accelerators usually have very low duty factors (the fraction of time when the beam is ‘on’). These small duty factors impose severe limitations on the radiation detection instruments based on particle-counting. The intense pulses usually overwhelm any active detector that detects particle events. Instruments which have long dead times, such as proportional and GM counters tend to become saturated in such fields. In the most unfavourable cases, pile-up of events may lead to the fact that only the repetition rate is counted. Also TEPCs can be used only with precautions because of pile-up effects (a random overlapping of pulses due to multiple events), which can lead to large systematic errors (see Section 2.3.1).

Scintillation survey meters may become nonlinear at higher dose rates because photomultipliers cannot handle the high instantaneous currents.

2.4.4 Active neutron detectors

Active neutron detectors belong to the class of particle-counting devices. One must distinguish between counters which are sensitive to thermal neutrons and are therefore used in spectrometers with moderator spheres like NEMUS (Section 5.8) or the CERN BSS (Section 5.9) and those which are based on the interaction of the unmoderated neutrons. In the region of intermediate neutron energies (a few keV to about 2 MeV) one uses proportional counters with hydrogen-containing gases such as CH_4 or with ^{4}He gas. For energies above 2 MeV up to about 10 MeV liquid or solid scintillators such as NE213, BC501A or stilbene have been used for spectrometry in workplace fields (for reference neutron fields, these devices were used up to 100 MeV). This report discusses mainly the properties and problems of high-energy neutron environments. Therefore we concentrate in this section on counters which are used in multisphere spectrometers which, if modified with metal shells, are sensitive also in the energy region above 20 MeV. Thermal detectors used in moderator spheres are ^{6}LiI scintillators or proportional counters filled with counting gases like ^{3}He or $^{10}BF_3$.

The general problem of active detectors was already mentioned in the preceding sections, namely that the intense and short pulses of neutrons just overwhelm the counter and the counting electronics behind it. To illustrate the problem arising from short but intense pulses, results are shown here from an experiment which can be treated as a simulation. From this example one can learn where the pitfalls are. The experiment was to measure the response of a ^{3}He proportional counter to a thermal Maxwell-like small-sized (3 cm × 3 cm) neutron spot. The counter was scanned through the neutron beam using a pseudo-Lissajous scanning procedure of total extension of 10 cm × 10 cm. That means that the counter sees neutrons for a short time and then there is a gap. The counts were recorded with a bin width of 80 ms and the result is shown in Fig. 11.

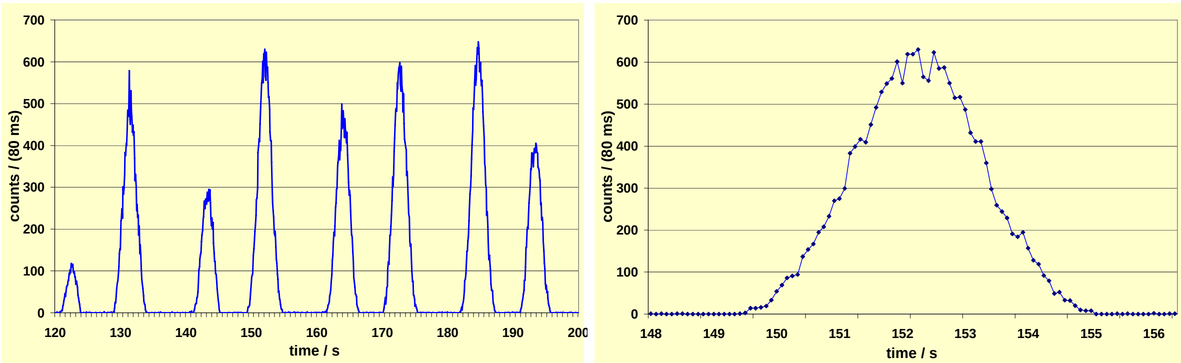

Fig. 11: Counts per 80 ms in a ^{3}He proportional counter while scanned through the neutron beam on a pseudo-Lissajous path (the right graph is a zoom of the fourth peak from the left)

Calculating the dead time correction using the total number of counts of the total measuring time (τ = 12 µs) results in a correction factor of f'_{DT} = 1.0101. But if the correction factor is calculated for each of the 10.000 bins of 80 ms bin width one gets values of up to 1.114 and the final, correct value for this run was f_{DT} = 1.0546. That means there was a systematic error of almost 4.5% in the count rate. Compared with what is expected at some measuring positions at high-energy accelerators the above experiment is very moderate. In addition, the above example only takes into account the dead time of the electronics (pre-amplifier, amplifier, ADC, multichannel analyser). Nothing is really known about the influence on the electrical field inside the counter due to a very large number of positive charged particles (protons and tritons from the ^{3}He(n,p)t reaction) and the electrons (from the ionizing process of the protons and tritons). Further investigations are needed in this field.

3 Monitoring at European accelerator facilities

3.1 Research institutes

This section briefly reviews the main high-energy European accelerator facilities (proton, heavy ion and electron accelerators, as well as synchrotron radiation sources) along with the way workplace monitoring is organized at each of them. For each facility there are two sections. The first briefly describes the facility with reference to the parameters which eventually dictate the composition of the radiation field at workplaces and are thus relevant for area monitoring: the accelerators, the particles accelerated and their energy range, the beam extraction mode (slow, fast) and the time structure of the beam. The second briefly discusses how area monitoring is organized and which instruments are employed.

3.1.1 CERN

CERN (the European Organization for Nuclear Research) operates a number of accelerators for fundamental and applied physics as shown in Fig. 12 [(72)]. The PS (Proton Synchrotron) complex installed on the Meyrin site of CERN consists of a number of accelerators and experimental areas. Linac 2 is an Alvarez Proton Linac, which provides pulsed (0.8 Hz) beams of up to 180 mA at 50 MeV to the PSB (PS Booster), with pulse lengths varying between 20 and 120 µs depending on the number of protons required by the user. A second linac (Linac 3) presently provides beams of $^{208}Pb^{54+}$ ions at 4.2 MeV/u to LEIR.

The low-intensity ion beam from Linac 3 is accumulated and cooled by electron cooling in LEIR, the Low Energy Ion Ring (formerly LEAR, Low Energy Antiproton Ring), and accelerated before being transferred to the PS, in order to obtain dense ion bunch useful for future LHC (Large Hadron Collider) ion operation. LEIR fast extracts 1 (early scheme) to 5 (nominal scheme) pulses of 1.15×10^9 $^{208}Pb^{54+}$ ions (for a total of 1.15–5.75 10^9 ions) at 72 MeV/u every 2.4 s (early scheme) to 3.6 s (nominal scheme).

The PSB, which is not part of the LHC ion injectors, consists of four identical rings on top of each other and accelerates protons to a kinetic energy of 1.4 GeV. Part of the PSB beam (up to 4×10^{13} p/pulse with a minimum repetition period of 1.2 s) is fast extracted towards ISOLDE (the On-Line Isotope Mass Separator), a facility dedicated to the production of a large variety of radioactive ion beams for a number of different experiments, e.g. in the field of nuclear and atomic physics, solid-state physics, life sciences and material science. The rest of the PSB beam is fast extracted and transferred to the PS. The beam intensity varies from 5×10^9 p/pulse to 4×10^{13} p/pulse with a minimum repetition period of 1.2 s. The pulse length can vary from few hundreds nanoseconds to approximately 2 µs.

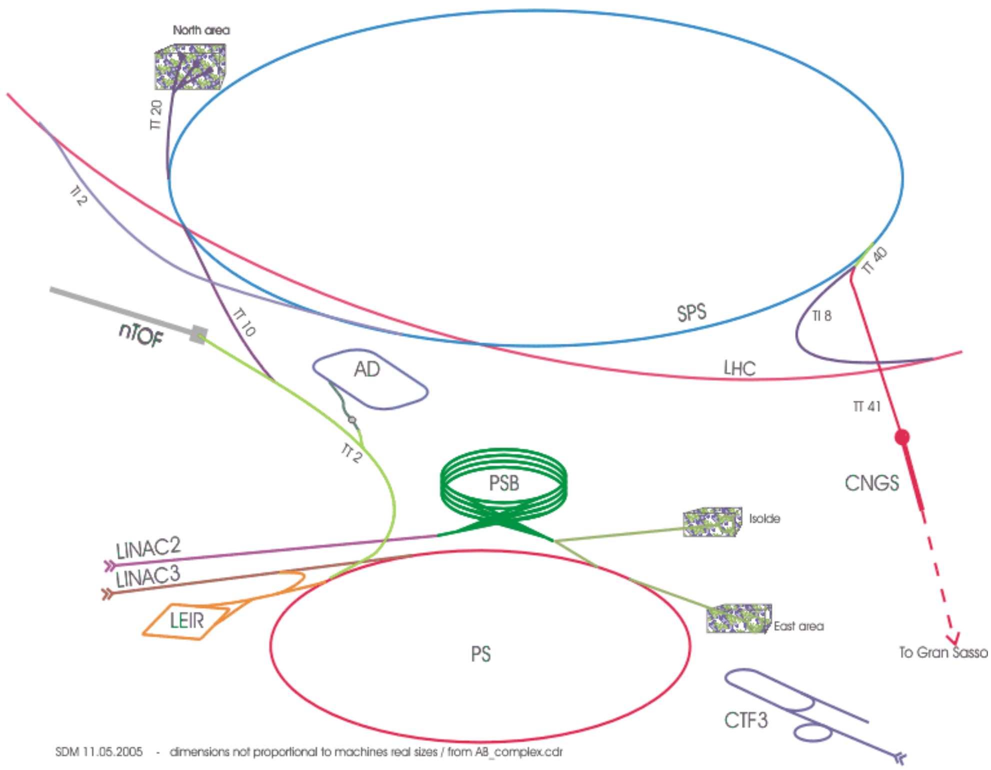

Fig. 12: The CERN PS-SPS-LHC accelerator complex

In the PS the proton beam injected from the PSB is accelerated to a momentum of up to 26 GeV/c. The PS beam can be either sent to the East Hall for fixed target physics experiments, to the AD (Antiproton Decelerator), to the n_TOF facility or to the SPS (Super Proton Synchrotron).

Experiments in the East Hall use slow extracted beams with 24 GeV/*c* momentum and intensity of up to 10^{11} protons per PS pulse. n_TOF uses a high-intensity (7×10^{12} protons per pulse) fast extracted beam (6 ns pulse width) at 20 GeV/*c* with a typical repetition rate of one pulse every 1.2 s. The beam is sent to a lead spallation target to produce neutrons over a wide energy range for a variety of experiments (such as cross-section measurements) using the TOF technique.

Part of the 26 GeV/*c* protons from the PS are sent to a target, converted into antiprotons with a momentum of 3.57 GeV/*c* and injected into the AD, where they are cooled by stochastic cooling and decelerated from 3.57 GeV/*c* to 100 MeV/*c*. The beam is fast extracted from the AD and sent to four experiments located in an area in the centre of the ring. The AD delivers 10^7 antiprotons every minute at bunch lengths between 200 and 500 ns. The experimental area is accessible during operation as the radiation levels are low.

The rest of the PS beam is transferred to the SPS via the TT2-TT10 transfer line either at 14 GeV/*c* (fixed target beam) or at 26 GeV/*c*.

The $^{208}Pb^{54+}$ ion beam is injected in the PS and accelerated to 6.7 GeV/*c*/u and then transferred to the SPS through the TT2-TT10 line. The beam is fully stripped in the transfer.

The SPS accelerates the proton beam for fixed target physics from 14 GeV/*c* to 400 GeV/*c*. The protons are presently slow extracted with intensity of about 3×10^{13} over a pulse length of a few seconds every 16.8 s and sent to a target area, where a number of secondary beams of lower energy and intensity are produced. At present these beams are exclusively used for fixed-target physics experiments and for testing detector components for the LHC experiments in the North Experimental Area on the Prévessin site of CERN.

As of 2006 the SPS sends 400 GeV/*c* protons to the CNGS (CERN Neutrinos to Gran Sasso) facility built underground. The beam is fast extracted from the SPS with intensity of 4.4×10^{13} protons (extracted in two pulses spaced by 50 ms and each 10.5 μs long) every 6 s for three times, followed by an interval of 17 s (during which the SPS provides beams for other uses). The beam strikes a target made of small graphite cylinders to produce a beam of pions and kaons. These particles decay in-flight producing muons and ν_μ. The muons are absorbed in the earth while the neutrinos travel to the Gran Sasso laboratory situated in central Italy at a distance of 730 km.

The SPS will be the final pre-injector for the LHC due to start operation in 2007. 450 GeV/*c* protons (up to 3.2×10^{13} p/pulse) will be fast extracted and transferred to the LHC every 21.6 s via the TI2 or TI8 transfer lines. The SPS will also deliver Pb^{82+} ion beams at 177 GeV/*c*/u, 9×10^7 ions per bunch (up to 52 bunches for the nominal scheme) every 50.4 s. After injection and ramping, in the LHC the beams will circulate for several hours and collide at the centre of four large experimental apparatus.

Working independently of the other accelerators is CTF3 (CLIC Test Facility), the main aim of which is to prove the feasibility of the RF power source design and to produce 30 GHz power at nominal CLIC parameters. The facility uses equipment from the former LEP injector. CTF3 is the only electron accelerator presently operating at CERN. Electrons are accelerated to 150 MeV in a linac, followed by two rings which multiply the bunch repetition frequency and compress the pulse length to 140 ns. The beam current of 35 A is then used to power a high RF power test stand for component development, and testing CLIC accelerating modules at the nominal gradient of 150 MV/m.

3.1.1.1 Radiation monitoring at CERN

Area monitoring at CERN is based on passive dosimetry (^{6}LiF/^{7}LiF thermoluminescent dosimeters – TLDs – under a 5 inch polyethylene moderator, to evaluate dose equivalent values integrated over a given period of time), and on-line monitoring using three types of ionization chambers (plastic, hydrogen-filled or argon-filled) and rem counters. The read-out of all monitors is sent to a central data acquisition system called ArCon (Area Controller). From a console one can view the location and status of each monitor, check and reset alarm levels, display and print (either in tabular or graphical form) the values of dose equivalent recorded over the past 72 hours (integrated over one hour period), or over a preceding period of time by interrogating a radiation database. The ArCon can also take any pre-defined data-dependent actions that may be needed, such as flashing a warning light or cutting off the beam. At present 400 monitors are connected to the system. These are installed in the accelerator tunnels, in the experimental areas and on the various CERN sites for ambient monitoring.

Stray radiation inside the accelerator tunnels and in the experimental areas is mainly monitored with Ar- and H-filled ionization chamber pressurized to 2×10^{6} Pa (20 bar). The former type is use to detect photons and charged particles (but recent studies have shown that they have a good sensitivity to high-energy neutrons [(73)]), the latter have a good sensitivity to neutrons, photons and charged particles. Ionization chambers are usually Centronics type IG5, but in pulsed fields type IG32 is employed. PTW ionization chambers filled with air at atmospheric pressure are mainly used to monitor induced radioactivity (X- and gamma-rays) in the accelerator tunnels. Environmental monitoring stations installed on the CERN site and at selected locations in the surrounding Swiss and French regions are equipped with rem counters (using a BF_3 counter) and Ar-chambers. Air and water releases are monitored with differential free-in-air ionization chambers and NaI scintillators, respectively. All monitors are checked annually and calibrated every three years in the calibration laboratory of the Radiation Protection group with Pu-Be, Am-Be and ^{137}Cs sources.

Accesses to all CERN sites are equipped with detectors provided with large area plastic scintillators, to monitor the passage of radioactive materials. The read-out of these detectors is also sent to the ArCon.

A new radiation monitoring system is presently been implemented for future LHC operation (see Section 5.3). Such a system will eventually be extended to the existing accelerators, replacing the ArCon.

3.1.2 GANIL (Grand Accélérateur National d'Ions Lourds)

GANIL is a French National User's Facility, built in the early 1980s, available to a wide national and international scientific community. Five cyclotrons are used for fundamental nuclear physics, but some experiments are also performed in the field of condensed matter and biology (Fig. 13) [(74)]. Stable ions ($A \geq 12$) like carbon with energies up to 100 MeV/u, or uranium at energies up to 24 MeV/u and radioactive ions are produced and accelerated [(75)]. The injector cyclotrons C01 and C02 deliver the ion beams to the CSS1 and CSS2 separate sector cyclotrons. CIME is a cyclotron used for accelerating stable and radioactive ions. The accelerated beams are then distributed to the various experimental areas shown in Fig. 13. The extraction mode of the ion beams is fast, with 10 MHz frequency and pulse width of about 5 ns. The characteristics of the accelerated beams are given in Table 2.

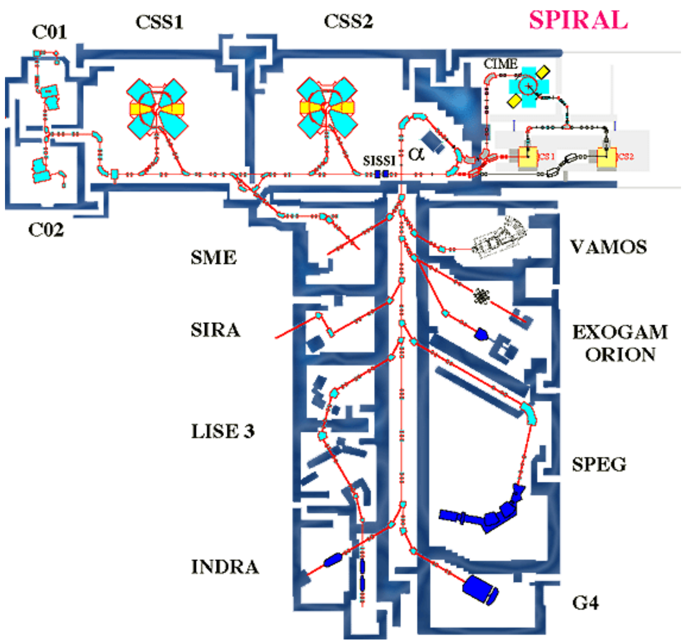

Fig. 13: Scheme of the GANIL cyclotrons and experimental areas

Table 2: Accelerated ions at GANIL

	GANIL cyclotrons			
	C01 & C02	**CSS1**	**CSS2**	**CIME**
Accelerated ions		Stable		Radioactive
Atomic mass of primary ions			≥ 12	
Atomic mass of secondary ions		—		Unlimited
Energy range of the accelerated ions	≤ 0.97 MeV/u	≤ 13.5 MeV/u	≤ 95 MeV/u	≤ 25 MeV/u
Intensity range of the accelerated ions	≤ 5×10^{14} pps	≤ 3×10^{13} pps	≤ 2×10^{13} pps	≤ 5×10^{11} pps

Inside the experimental areas, neutron ambient dose equivalent monitoring is performed with SAPHYMO CINN32 survey meters. These instruments are active devices consisting of an ^{3}He thermal counter placed in a moderator. Ionization chambers SAPHYMO – CIEP 42 are used for photon dose monitoring. Outside the experimental areas, some passive dosimeters, PN1+PN3 from IRSN and FLi pellets are placed on the concrete shielding walls.

Access to the experimental areas is not allowed during operation, due to stray neutron radiation coming from the interaction of the ion beam with beam line elements, the energy range of which extends from thermal to about 100 MeV. Behind the shielding the neutron fluence is quite low.

No modelling of the facility and no development of survey meters is performed at GANIL. The neutron spectra behind the shielding were neither measured nor calculated.

3.1.3 PSI (Paul Scherrer Institut)

The Paul Scherrer Institut (PSI) at Villigen, Switzerland is a multi-disciplinary research centre for natural sciences and technology. It is one of the world's leading user laboratories for both the national and international scientific community, and also participates in national and international collaborations with universities and industry. The research priorities of the institute lie in the area of basic and applied physics. In order to cover the broad range of experimental possibilities the institute operates several beam facilities.

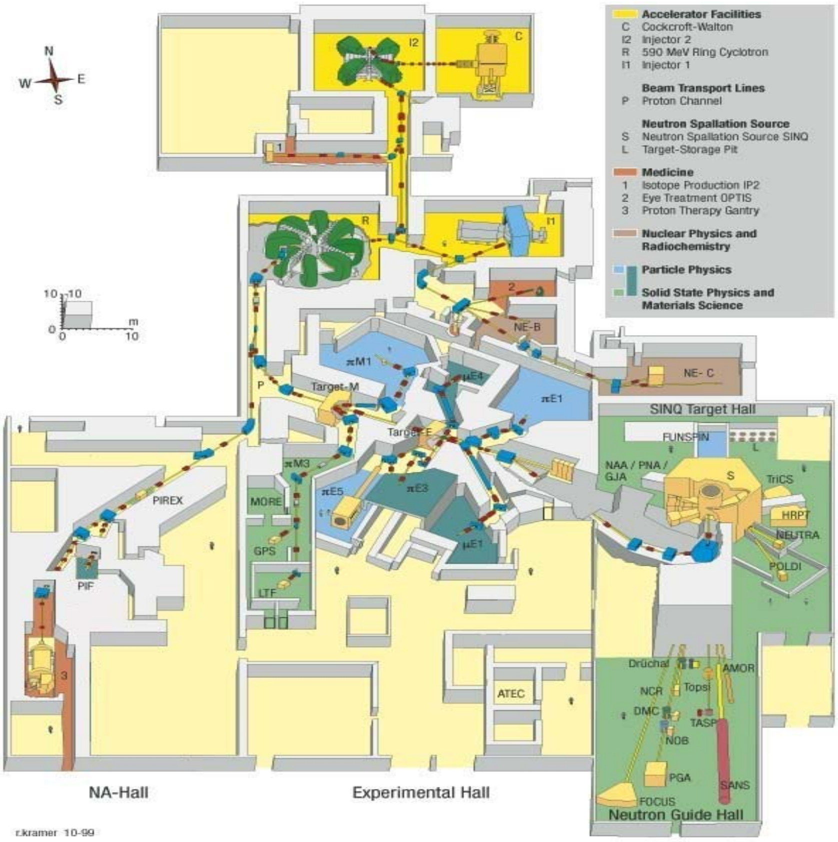

Fig. 14: View of the PSI proton accelerator facilities

The proton accelerator facilities (Fig. 14) with the high-intensity Ring Cyclotron built by PSI and commissioned in 1974, are one of the central research installations. The generation of the 1.8 mA 590 MeV proton beam with beam power greater than 1 MW is divided into three steps. The protons generated by an ion source are first accelerated to about 870 keV by a Cockroft Walton pre-injector. During the second step they are accelerated to 72 MeV in a sector magnet ring cyclotron (Injector 2). The final acceleration to 590 MeV is performed in a separated sector cyclotron (50.63 MHz accelerator frequency). Presently the extracted beam current (0.03% extraction losses) is 1.8 mA, a current upgrade to 3 mA is planned and should be completed in 2010 (without operation breaks apart from the annual maintenance shutdown).

The extracted proton beam is transported to a splitter magnet. Here the major part of the beam is directed onto two consecutive meson production graphite targets (Target M and Target E). The pions and the muons resulting from their decay are guided to the various experimental areas located in the experimental hall. These particles are well known probes for the examination of fundamentally and technologically relevant effects in solid-state physics, as for example the structural magnetic or electronic phenomena in magnetic materials.

The proton beam passing the two targets is either defocused and stopped in a high power beam dump, or refocused and guided onto a heavy metal target in the Spallation Neutron Source (SINQ) located in the SINQ Target-Hall. During the resulting spallation reactions primarily evaporation neutrons are released from the highly excited target nuclide. A D_2O and a liquid D_2 moderator tanks provide neutron guides for the horizontal extraction of the thermal and cold neutrons. SINQ is a continuous source – the first of its kind in the world – with neutron fluence rate up to 10^9 cm^{-2} s^{-1} at the different PSI instruments. Neutron scattering experiments are performed to give insight into atomic structures and short time dynamics. Neutron physics covers a broad range of applications from physics to chemistry and biology.

Other applications of the proton facility are human cancer therapy (see Section 3.2.3), the development of new products for medical diagnosis, therapy and material research using neutrons and muons.

Since the year 2001 a 2.4 GeV synchrotron radiation source (SLS) is operating, providing high quality photon beams for research in material science, chemistry and biology. The production of the electrons to be accelerated to 2.4 GeV is performed by a 90 keV triode with Pierce geometry. The electron gun is followed by a linear accelerator. Here the beam is bunched and accelerated to 100 MeV in a two-step procedure. The 100 MeV electron pulses are injected by a fast kicker magnet into a booster ring of 270 m circumference having an accelerator cycle of 3 Hz. Having reached the nominal energy of 2.4 GeV, the electron pulses are injected into the storage ring of 288 m circumference, in which they circulate for several hours. The nominal current is 400 mA (multibunch mode) and the charge per bunch of 1 mA is 0.96 nC. Synchrotron radiation losses are compensated by a 200 kW, 500 MHz high frequency cavity. Both the linac and the booster storage ring are located in a shielded concrete tunnel. The synchrotron radiation generated by insertion devices (wigglers, undulators) is guided to the experimental hutches. The frequency range covered by the machine lies between ultraviolet and hard X-ray, allowing structural analysis of surfaces and inner regions of various materials.

3.1.3.1 Radiation monitoring at PSI

Swiss radiation protection regulations give the limits of radiation exposure in the controlled radiation areas accessible by personnel under dosimetric control, as well as for normal unrestricted areas close by. Passive dosimeters are employed for both the personnel and the facility/area dosimetry. TLD-badges are used to measure individual γ-dose equivalent $H_p(10)$ and $H_p(0.07)$, whereas CR-39 badges, equipped with special radiators to increase sensitivity, provide the individual neutron dose equivalent $H_p(10)$. The facility/area ambient dose equivalent $H^*(10)$ dosimetry nets consist of about 260 measuring positions. The γ-dose is accumulated by AL_3O_2 and ^{7}LiF based TLDs, whereas the neutron dose is integrated by fission track dosimeters (^{235}U converter in moderator and ^{232}Th converter, respectively). The readings are reported quarterly to the authorities, the Swiss Department of Public Health and the Swiss Federal Nuclear Safety Inspectorate.

Online monitoring of the ^{3}H and β^+ activity in the air is performed by measurement setups using ionization chambers (LB 671, Berthold Technologies), NaI detectors (using 20l PSI-measuring chamber and LB5310, Berthold Technologies) as well as γ- and neutron-dose rate monitoring by GMZ (GammaTRACER, Genitron Instruments) ionization chambers (PTW type 34031 and IG5 by Centronic Ltd.) and ^{3}He (LB6411, Berthold Technologies) respectively BF_3 proportional counters (2202 B, Alnor (Studsvik)). The resulting facility-dependent radiological data are gathered and distributed to the different facility control rooms by a sophisticated MEVIS-system. Online-data as well as history-files are available. Local optical/acoustical alarm units create warnings in case of radiological hazards.

Access to the experimental areas and the facility vault silos is controlled by personnel safety equipment, mainly using ionization chambers for monitoring of the stray radiation fields. If demanded by the radiological situation also β^+ and ^{3}H activity levels are evaluated. The systems also interact with the machine emergency shut down system.

The limits for the radioactivity released by the exhaust air stacks are given in PSI's operating approval, those of the effluents by the Swiss radiation regulatory body. Radioactive aerosols in the exhaust air are gathered by filters evaluated by Ge detectors and ^{3}H activity by elution systems followed by liquid scintillation. Accounting is done weekly, while gaseous radioactivity is measured online. Effluents from controlled areas are directed to collecting tanks being under radiological control by Ge-detectors and liquid scintillation.

3.1.4 TSL (The Svedberg Laboratory)

The Svedberg Laboratory (TSL) in Uppsala, Sweden, is a cyclotron facility with a reputed mission in proton radiotherapy, interdisciplinary research and commercial irradiations. An overview of the laboratory is shown in Fig. 15. The Gustaf Werner cyclotron is providing a wide range of ion beams of various energies up to 180 MeV for protons and 8 MeV/u for xenon ions. The cyclotron has an internal PIG ion source for the production of light ions and an external ECR ion source for multiply-charged heavy ions.

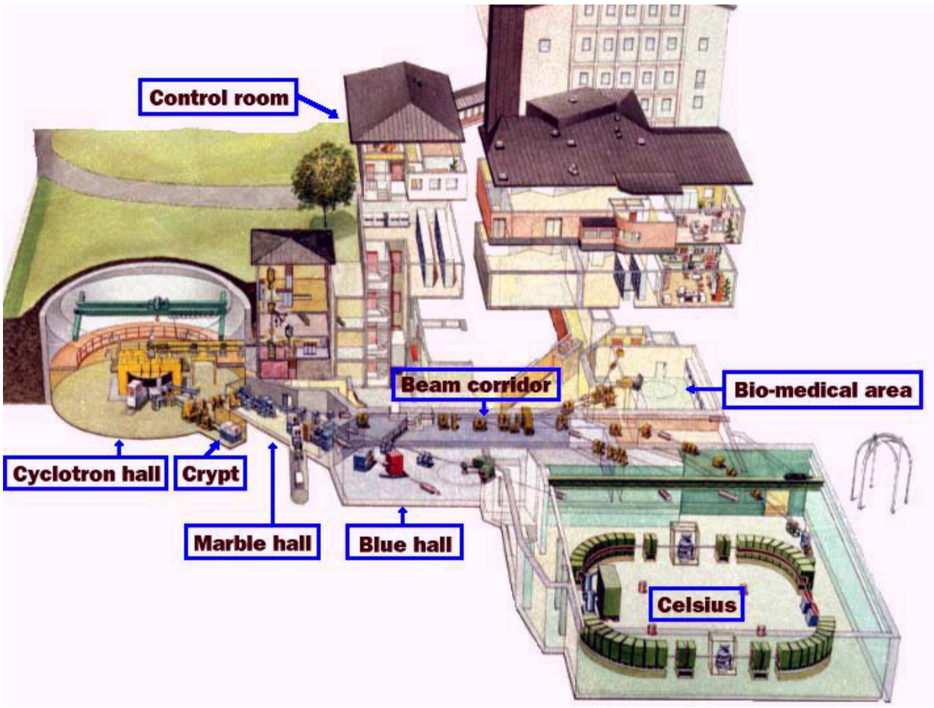

Fig. 15: General layout of TSL

A main fraction of the beam time at TSL is devoted to radiotherapy of cancer patients with 180 MeV protons. Since the treatment time for each patient normally is very short, more than 80% of the beam time may be used for other projects during the radiotherapy weeks. High-intensity proton beams are used for radionuclide production for medical applications, whereas light ions with energies up to 45 MeV/u are used by several groups studying the effects of high-LET irradiation on the induction of cell death and DNA fragmentation.

The materials-physics experiments at TSL are mainly using the heavy-ion beams from the cyclotron. A remotely controlled irradiation facility has been installed, giving homogeneous irradiations of 40×40 mm^2 samples by beam scanning. Several projects within ion-track-based nano- and micro-technology profit from this installation.

There is a long-term experience in high-energy neutron production at TSL. A neutron facility was built first in the late 1980s and remained in operation until 2003. In 2003–2004 a new facility was constructed where emphasis was put on high neutron-beam intensity in combination with flexibility in energy and neutron field shape. The facility uses the ^{7}Li(p,n)^{7}Be reaction to produce quasi-monoenergetic neutron beams. The cyclotron provides proton beams in the energy range 25–180 MeV resulting in neutrons with peak energies controllable in the 20–175 MeV range. A general view of the neutron-beam facility is given in Fig. 16. The neutron beam is formed geometrically by iron collimators with holes of variable sizes and shapes. The user area extends from 3 m to 15 m downstream of the lithium target. Neutron-beam intensities up to 5×10^5 cm^{-2} s^{-1} are obtained.

Commercial neutron and proton irradiations for industrial users studying single-event effects in electronic components represent a large and growing activity at TSL. In addition, two experimental stations, MEDLEY and SCANDAL, are available for research projects with neutron-induced reactions. Moreover, the neutron beam facility has frequently been used for dosimeter development research.

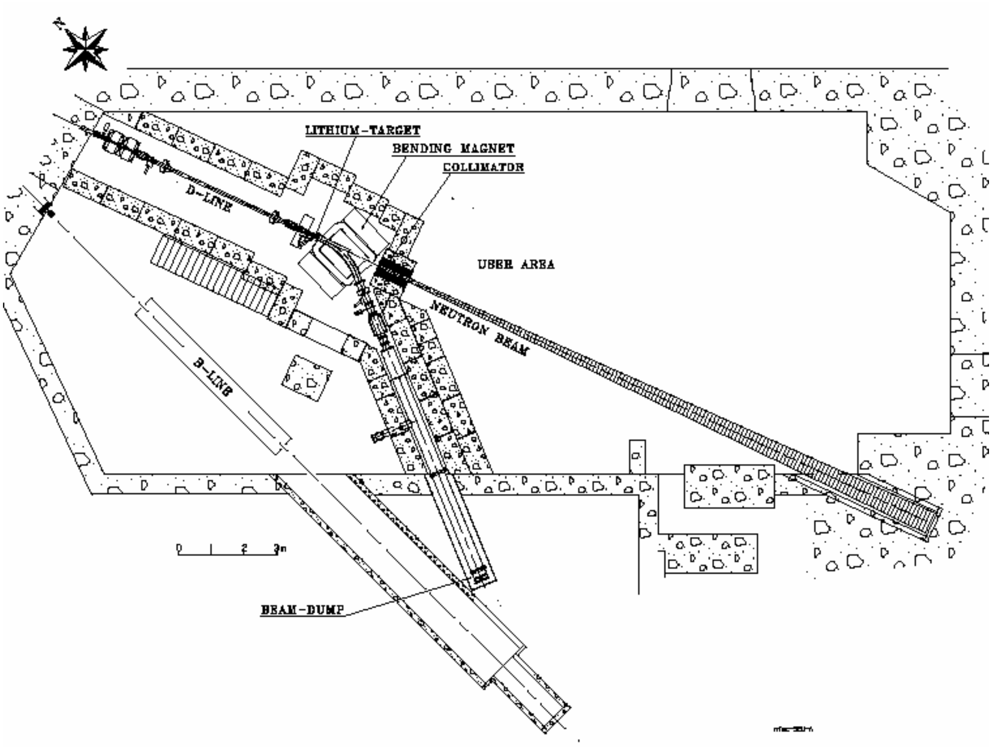

Fig. 16: General layout of the neutron-beam facility at TSL

3.1.4.1 Radiation monitoring at TSL

The radiation protection at TSL is based on safety interlocks, permanent detectors and personal dosimeters. An area must be cleared of people with a special clearing procedure before high-energy beams can be let into that particular area. When the clearing procedure is initiated both an acoustic alarm and red lights are activated in the area. After the clearing procedure is completed, red lights on the display at the entrance indicate that access is forbidden and that the beam is allowed to enter the area. In all areas with accelerators and/or beam lines there are acoustic alarms and rotating warning lamps installed. In case the dose rate in the area rises above 10 mSv/h the acoustic alarm sounds.

The concrete walls surrounding the experimental sites are thick enough to assure the safety of those nearby in most circumstances. Permanent detectors are placed in experimental areas so that radiation levels can be checked. These detectors continuously measure the gamma and neutron radiation levels in sections where there is no beam. Gamma rays are monitored using energy-compensated GM-tubes, and neutrons are detected with Li-glass detectors, surrounded by plastic moderators.

Personal electronic dosimeters, RAD-52, are mandatory for work in experimental areas. These are sensitive to gamma radiation and provide direct information as to the integrated photon dose and thereby the strength of the radiation field. The RAD-52 functions as an alarm when used in areas with high radiation levels, i.e., when the dose rate exceeds 100 µSv/h.

3.1.5 GSI (Gesellschaft für Schwerionenforschung)

The GSI (Gesellschaft für Schwerionenforschung) accelerator laboratory in Darmstadt, Germany, delivers all types of ion beams, up to and including uranium in any state of electric charge. The facility can also be used to create and accelerate beams of radioactive nuclei. The research performed at GSI covers fundamental nuclear physics, physics of the atomic shell, material research, plasma physics, biophysics and cancer therapy with ions. The accelerator consists of three facilities (Fig. 17):

- UNILAC (Universal Linear Accelerator). The ion beams have energies up to 14 MeV/u, pulse lengths from 150 µsec to 5.5 ms, and duty factors from 1‰ to 27.5%. Examples are Cr ions with intensity of 4.9×10^{12} ions per second (27.5% duty cycle, 20 µA per pulse for $^{54}Cr^{7+}$) or U ions with intensity of 5×10^{12} ions per second (25% duty cycle, 90 µA per pulse for $^{238}U^{28+}$),
- SIS18 (Heavy Ion Synchrotron, magnetic rigidity of 18 Tm). The ion beams have energies up to 1–2 GeV/u, the beam intensity is in the range e.g. for uranium beams of 10^{11} ions per second at 200 MeV/u to 10^{10} ions per second at 1 GeV/u. The spill length varies from 100 ns (fast extraction with bunch compression) to 10 s for the slow extraction. The intensity in the slow extraction mode is modulated, which can be described with frequencies from 150 Hz to 4 MHz,
- ESR (Experimental Storage Ring, magnetic rigidity of 10 Tm). Storage of ions and radioactive beams is possible in this facility. A total number of 10^9 ions are stored and a filling rate up to 10^8 ions per second or more can be chosen. The beam loss rates are very low in the normal operation. Beam losses can occur during the filling process with the above mentioned intensities and have a time structure which is given by the synchrotron extraction (SIS18).

Beside the main accelerators UNILAC, SIS and ESR are the in-flight facility FRS for the production of rare isotopes, the experimental areas Cave A, B, C, H (Hades, experiments with pions) and the radiotherapy Cave M.

At the UNILAC experiments are carried out in the hall for low-energy experiments (EH) in the straight beam line. Beams are transferred via the transfer channel to the SIS. From the SIS the beams are delivered to the FRS, the ESR, pion production target or directly to the experiments (Target Area).

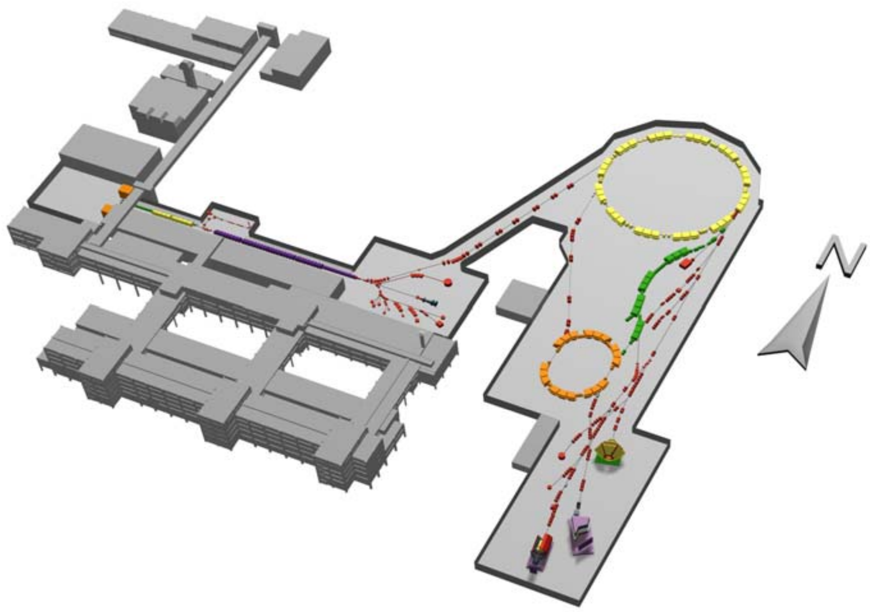

Fig. 17: View of the GSI facility with the UNILAC, SIS and ESR accelerators

3.1.5.1 Radiation monitoring at GSI

Area and workplace monitoring is performed using rem counters of the Andersson–Braun type (Biorem, Thermo electron) for neutron radiation and with proportional counters for gamma radiation (FHZ 600, Thermo electron). Additionally moderated TLDs containing $^{6}Li/^{7}Li$-fluoride crystals are employed. The neutron radiation mainly extends up to 1–4 GeV in the SIS/ESR/TH area and up to about 20 MeV in the UNILAC area. The gamma radiation during accelerator operation is measured with ionization chambers and proportional counters. The main occupational radiation exposure at GSI comes from activated structures in the experiments and the structures of the accelerator by beta- and gamma-emitters.

Research is done on the response of active and passive neutron dosimeters (for area monitoring). The response of the instruments is investigated experimentally in reference neutron fields at CERN and at PTB, and in Cave A at GSI. Furthermore, response functions are computed using Monte Carlo based radiation transport codes like FLUKA and MCNP.

A moderated thermoluminescent detector has been developed. The instrument consists of a spherical moderator made of polyethylene with a layer of lead serving as a spallation target for high energetic neutrons and a thermoluminescent card in the centre of the sphere. The card is carrying four lithium-fluoride crystals, two with ^{6}Li (sensitive to low-energy neutrons) and two with ^{7}Li. The instrument is used to measure the ambient dose equivalent in neutron fields of varying energy. The response function has been computed and experiments are under way to verify the energy dependence of the response. The instrument is routinely calibrated with a 37 GBq ^{241}Am-Be neutron source. Further optimization of the neutron moderating and multiplying layers is planned for the future.

3.1.6 The ELETTRA synchrotron light source

ELETTRA is a third generation synchrotron radiation facility operating in Trieste (Italy) since 1994. The accelerator complex is composed of a 1.2 GeV linac used as injector and a 2–2.4 GeV storage ring. The linac, placed in an underground tunnel, includes in the first part the electron gun, the chopper and the buncher, and a first section where electrons are accelerated up to 100 MeV. In the second part, consisting of seven sections, the electron energy is increased to 1.2 GeV. In the storage ring the energy can be ramped up to 2 GeV or 2.4 GeV. The maximum ring current is 320 mA at 2 GeV and 160 mA at 2.4 GeV. The ring is composed of 12 achromats, each one with two bending magnets, and has an equivalent circumference of 259.2 m. The 12 straight sections of the machine, 6 m long, house the insertion devices.

The facility is optimized to produce synchrotron radiation in the energy band of VUV and soft X-rays; however there are also several hard X-ray beamlines in operation or under construction. To improve synchrotron beam stability, a new injector is under development to allow full-energy injection into the ring and to maintain the beam current at a high level operating in regime of frequent injection (‘top-up’). The new accelerators will consist of a 100 MeV linac and a booster synchrotron, where the electron energy will be raised to 2.5 GeV before the beam is injected into the storage ring. Once the new injector enters in operation the present 1.2 GeV linac will be employed in the development of a new FEL facility (FERMI project).

At present there are 19 operating beamlines, two beamlines under commissioning and four additional under construction.

3.1.6.1 Radiation monitoring at ELETTRA

Environmental radiation monitoring

The radiation monitoring system around the accelerators is based on several gamma and gamma/neutrons stations located at various positions in the Experimental Hall and in the Service Area and connected to a personal computer via a local network (Fig. 18). Each unit consists of an environmental ionization chamber for gamma dose and of a BF_3 counter for the neutron component. Measurements of average and maximum dose rates are recorded by a personal computer.

Gamma detector characteristics
Model: Centronic Mod. IG5
Type: pressurized ionization chamber
Energy range: 80 keV–2 MeV
Energy response: ± 5% (120 keV–2 MeV)
± 20% (80 keV–120 keV)
Dose equivalent rate range:
0.01 μSv/h–0.01 Sv/h

Neutron detector characteristics
Model: FAG Biorem
Type: Rem counter (BF3 counter tube)
Energy range: 0.025 eV–15 MeV
Dose equivalent rate maximum: 0.4 Sv/h

Fig. 18: A gamma/neutron radiation monitoring station at ELETTRA

Bremsstrahlung gamma rays produced in the gas of the machine straight sections are monitored by gamma ionization chambers similar to the previous one, placed:

– as close as possible to each beam exit port outside the front-end hutch, downstream of the first optics component, or
– at the end of each beamline, if it is aligned with the machine straight section.

These monitors are interlocked with the beam stoppers for the gas bremsstrahlung of the beamlines and with the injection system of the ring. If a monitor measures a dose rate higher than a pre-fixed pre-alarm threshold, the beam stopper of that beamline is automatically closed; if the alarm threshold is exceeded too, injection is also stopped.

Data obtained from these monitors show that radiation levels measured in the experimental hall around the users' stations are comparable with natural background. Radiation levels detected in the supervised areas of the laboratory are largely below the maximum allowable annual dose of 6 mSv.

A second type of environmental dosimetry is performed with TLDs based on LiF (Mg, Cu, P). The dosimeters are read and substituted monthly. At present there are about 90 monitoring locations around the machine and inside laboratories working with X-ray generators or diffractometers.

Internal beam loss monitors

A network of gamma detectors is installed inside the machines tunnels (10 detectors in the linac, 5 in the transfer line and 24 in the ring) for machine diagnostic purposes (beam losses detection). These monitors have been developed and assembled at the ELETTRA laboratories. Each unit consists of a Si detector, a charge sensitive amplifier, an integrator, a logic circuit, a power supply and a line driver. The acquisition system is fully integrated with the ELETTRA Control System.

3.1.7 LNF (Laboratori Nazionali di Frascati)

The Frascati National Laboratories of the Italian Institute of Nuclear Physics (INFN) operates the DAΦNE accelerator complex for fundamental and applied physics. Fig. 19 and Fig. 20 show a general view and a schematic layout of the facility. The DAΦNE (Double Annular Φ Factory for Nice Experiments) consists of a linac for electrons and positrons with energy of 800 MeV and 550 MeV, respectively, an Accumulator ring for topping up and two Main Rings with energy of 510 MeV per beam.

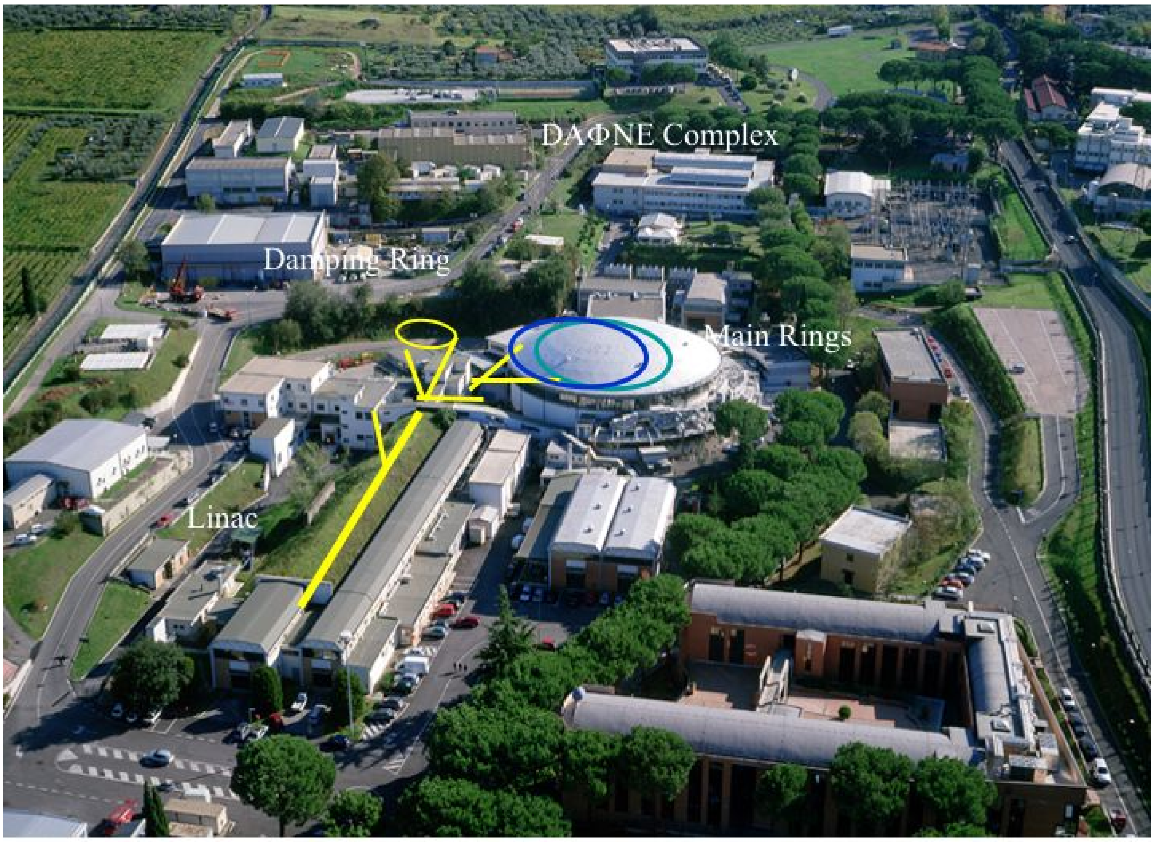

Fig. 19: General layout of LNF

The aim is to accumulate in the Main Rings two electron/positron beams with maximum intensity of 10^{13} particles/beam, divided in 120 bunches (average current 5 A) at 510 MeV. The linac also operates at energy of up to 800 MeV at low-intensity in order to generate a calibration beam (maximum intensity 10^{10} e^- per second, at the moment only 10^3 e^- per second are allowed) for the Beam Test Facility (BTF).

During normal injection of a single positron bunch, the linac injects into the accumulator 45 pulses at 20 ms intervals at 510 MeV. Electron injection is performed at a frequency of either 1 or 5 Hz. In both cases, the beam is “cooled” in the Accumulator for at least 100 ms and it is subsequently transferred into one of the Main Rings. This single bunch operation is repeated 120 times until the ring is completely filled. Nevertheless it is sometimes necessary to inject, for instance, half of the current per bunch over 240 times. In any case, during the injection cycle the maximum stored charge remains constant. The main parameters of the DAΦNE linac are listed in Table 3.

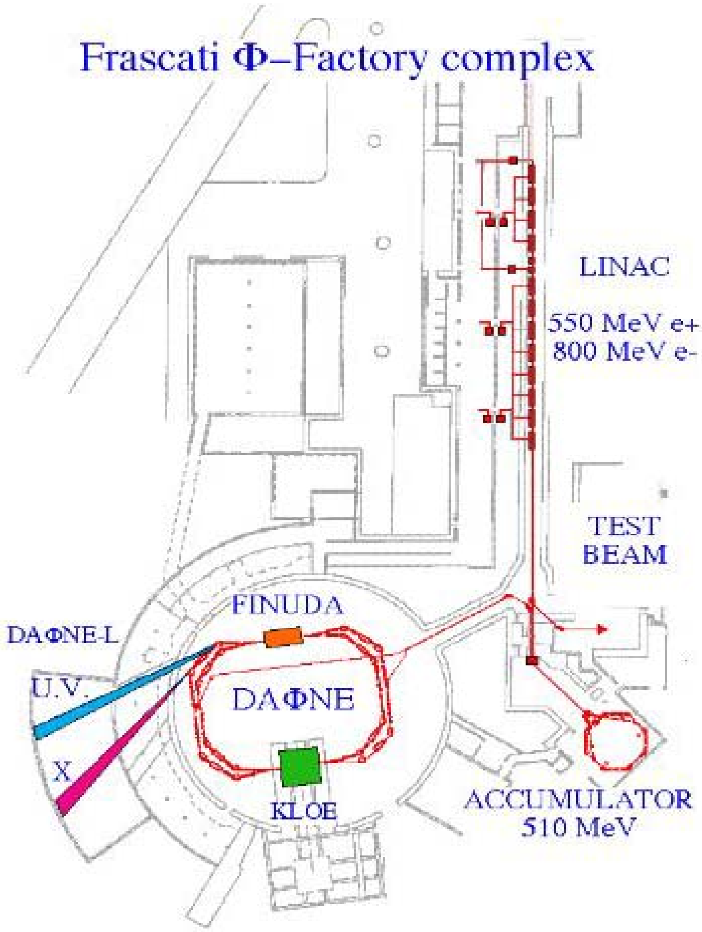

Fig. 20: Schematic layout of the DAΦNE accelerator complex

Table 3: Main parameters of the DAΦNE linac

Parameter	Value
Energy range	50–800 MeV (e^-) 50–550 MeV (e^+)
Transverse emittance at 510 MeV	1 mm mrad (e^-) 5 mm mrad (e^+)
Energy spread at 510 MeV	1% (e^-) 2% (e^+)
Repetition rate	1–50 Hz
Pulse duration	10 ns
Maximum current	500 mA/pulse (e^-) 100 mA/pulse (e^+)

The Linac is also used for electron and positron beam delivering to the DAΦNE BTF. The BTF is a beam transfer line optimized for the production of particles, in a wide range of multiplicities and down to a single electron mode, in the energy range between 50 and 800 MeV (550 MeV for positrons). The typical pulse duration is 10 ns and the maximum repetition rate is 50 Hz. The facility design has been optimized for detectors calibration purposes. The main parameters of the DAΦNE BTF are listed in Table 4.

Table 4: Main parameter of the DAΦNE BTF

Energy range	50–800 MeV e^-/e^+ (550 MeV)
Maximum repetition rate	50 Hz
Pulse duration	1–10 ns
Current/pulse	1 to 10^{10} particles/second
Allowed current	10^3 particles/second

3.1.7.1 Radiation monitoring at LNF

Area monitoring at LNF is based on passive dosimetry (^{6}LiF/^{7}LiF TLDs) under a polyethylene moderator and CR39 based dosimeters, as well as on active dosimetry (conventional and extended range rem counters) and on-line monitoring using ionization chambers (Centronic IG5) and conventional rem counters. An active Bonner Sphere Spectrometer, based on a 4 × 4 ^{6}LiI(Eu) scintillator and a set of seven polyethylene spheres (density 0.95 g cm^{-3}, diameters 2", 3", 5", 8", 10", 12" and an additional 12" sphere with a 1 cm lead insert) has been recently characterized and experimentally validated in radionuclide based reference fields. A customized neutron unfolding code, FRUIT (FRascati Unfolding InTeractive code), has been written especially for the needs of the neutron monitoring around DAΦNE. The measured neutron spectrum in a recently characterized test position outside the DAΦNE building in shown in Fig. 21. The LNF BSS has been also adapted to work with passive ^{6}LiF/^{7}LiF TLD pairs and, for high intensity fields, with activation gold foils.

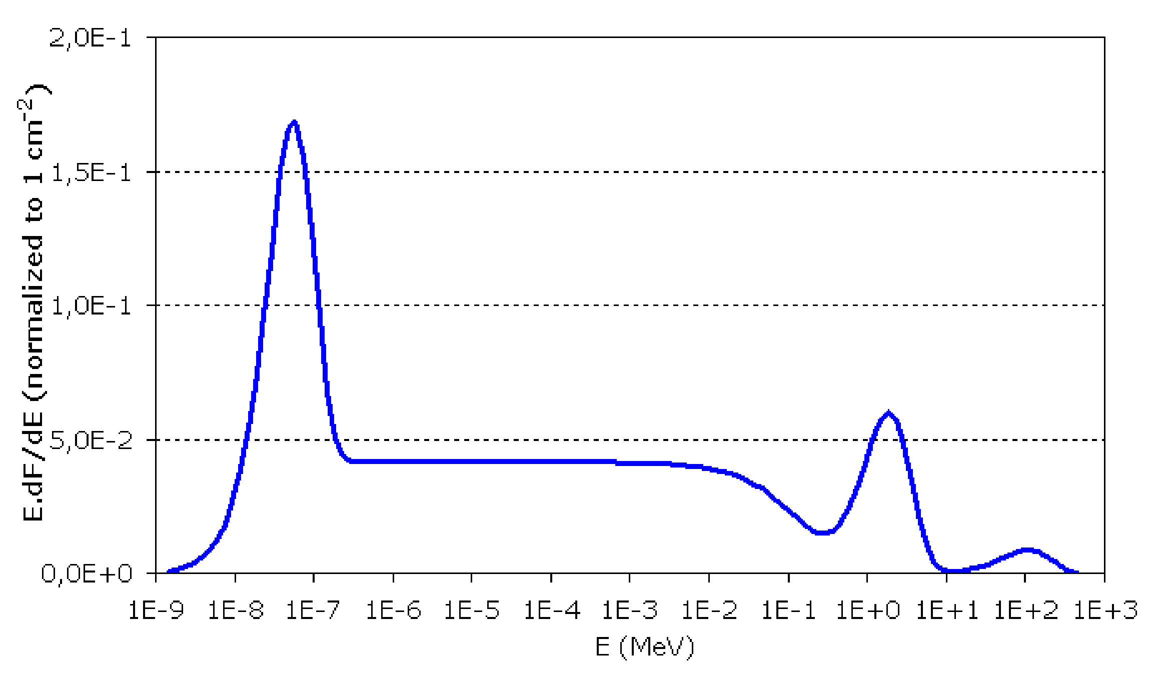

Fig. 21: Neutron spectrum measured around the DAΦNE Main Rings (normalized to unity integral and in equilethargic representation)

3.1.8 CCLRC (Council for the Central Laboratory of the Research Councils)

The Council for the Central Laboratory of the Research Councils (CCLRC) manages Rutherford Appleton Laboratory (RAL) and Daresbury Laboratory (DL). These laboratories provide large scale experimental facilities for the UK and international users. The facilities include the ISIS neutron spallation source and the Central Laser Facility (CLF) at RAL and the Synchrotron Radiation Source (SRS) at Daresbury Laboratory (DL). These facilities are described in the following sections.

3.1.9 ISIS at RAL (Rutherford Appleton Laboratory)

ISIS is currently the world's most intense, pulsed neutron and muon source. The facility (Fig. 22) provides beams of low-energy neutrons and muons for experiments across a diverse range of science disciplines. Typically, these experiments involve condensed matter, advanced engineering materials and bio molecular systems. Up to 1600 scientists per year are involved with experiments at ISIS. The facility was commissioned in 1984 and has 19 neutron beam lines and 7 muon beam lines. A second target station will be completed in 2008 providing initially 7 new neutron beam lines with a capability for 24 in the future.

The production of the 240 kW, 800 MeV, 50 Hz proton beam is achieved by using a radio frequency cavity to accelerate 23 mA of H^- ions to 35 keV with a pulse rate of 50 Hz. A Linac then further accelerates the ions to 70 MeV at which stage they are injected into a synchrotron. The ion beam is stripped of electrons and the remaining protons are bunched and accelerated to 800 MeV by 10 radiofrequency cavities. Protons are extracted towards an intermediate target and a main tungsten target to produce muons and neutrons respectively. The beam intensity is 3.75×10^{13} protons per pulse and the pulse structure consists of two 100 ns sub pulses.

Beam losses at 170 µA are: 1% for injection, 5–10% for trapping and acceleration, 0.02% for extraction and 0.1% for transport to the target. Transport line losses caused by the muon target are 5%.

Neutron production rates are up to 4×10^{14} neutrons per pulse with a spallation energy spectrum up to 800 MeV. The average neutron energy of about 2 MeV is moderated by liquid hydrogen, water and liquid methane moderators to produce pulsed, very low-energy, neutron beams for the experimental programme. The reliability of the ISIS facility is better than 90% and the accelerator operates for some 3500 hours per year.

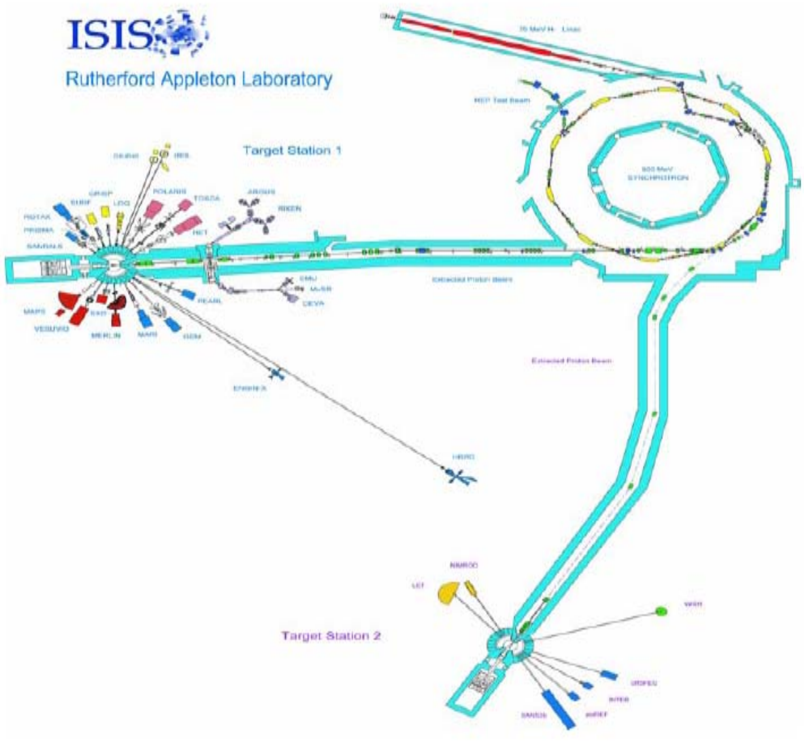

Fig. 22: ISIS at Rutherford Appleton Laboratory

3.1.9.1 Radiation monitoring at ISIS

The monitoring programme for ambient radiation and contamination hazards follows the principle of 'defence in depth' by using multiple measurement envelopes commencing at the source and extending beyond the site boundary. Active and passive methods are used. It should be noted that this programme is in addition to a monthly passive personnel dosimetry programme and routine area surveys carried out by Health Physics Assistants. There is also a small programme of measurements for skyshine source term validation and development of an irradiation facility for the electronics industry.

Linac, synchrotron and extraction line losses are monitored and controlled primarily by a beam loss monitoring system covering all of the beam transport system. These are 3 – 4 metre long Argon gas filled ion chambers at 1.2 atm and operated in a continuous current mode. The proton beam is tripped by this system within 400 µs (a faster in-line intensity monitoring system can trip beam within 60 µsec or 3 beam pulses).

The Linac also has five ion chamber gamma monitors inside the Linac tunnel adjacent to the accelerating tanks to detect excessive X-ray radiation from radiofrequency induced bremsstrahlung.

Ten, polyethylene moderated, neutron ion chambers with BF_3 tubes are located, external to all shielded areas, near access points. The monitors are Harwell rem type, operating in continuous current mode. These are used to provide local alarms during high loss conditions.

Beam lines, radioactive ventilation plant, manipulator rooms, radioactive workshops, active materials stores, waste storage areas and the transport receipt/despatch bays all have installed, local gamma, Geiger Müller tube radiation monitors that alarm at preset levels.

Passive environmental radiation monitors, utilizing CR39 and OSL TLD, are located at all experimental beam line cabins, the Linac hall, near stacks, in selected offices inside surrounding buildings and on the perimeter fence. Monitors inside buildings are analyzed monthly.

Environmental contamination monitors utilizing large Geiger Müller tubes, large 7 l Aloka ion chambers and gas bubbler systems monitor or sample all radioactive stack discharges. Four passive air sampling monitors using silica gel, located near the perimeter fence, are analyzed monthly for environmental releases.

Water and silt samples from boreholes, cooling towers and nearby ponds are analyzed, quarterly, for gamma and beta emitters.

3.1.10 CLF (Central Laser Facility) at RAL

The Central Laser Facility is a leading centre for research using lasers. The facility provides laser beams for experiments across a diverse range of science disciplines such as biology, chemistry and physics. A high-intensity laser programme is carried out with both ASTRA and VULCAN laser systems. These lasers produce high-energy electrons, bremsstrahlung photons, protons, heavy ions and neutrons in very short pulses.

The ASTRA laser is a TiS system which provides pulses of 40 fs duration with energies of typically 0.5 J per pulse and repetition rates of up to 10 Hz, providing power densities of 10^{19} W/cm^2 focussed onto targets. This will be upgraded in 2007 to produce Petawatt pulses from two beams of 30 fs duration with a pulse rate of 1 shot per minute, giving up to 10^{22} W/cm^2. The spot size diameter will be 3.5 µm.

VULCAN, commissioned in 2003, is a Nd:Glass laser system utilizing an Optical Parametric Chirped Pulse Amplification (OPCPA) front end. The facility provides pulses to multiple high-intensity target areas. The 100 TW target area operates with a 1 ps duration pulse with energies up to 150 J, delivering intensities of mid 10^{19} W/cm^2. This beam line is coupled to 6 long pulse beam lines capable of delivering a combined energy of 1.2 kJ in 1 ns, and can fire at a maximum repetition rate of 1 shot every 20 minutes. The Petawatt Target area operates with a 500 fs pulse duration and energies up to 500 J, delivering 1 Petawatt and capable of reaching focussed intensities of 10^{21} W/cm^2 in a spot size of around 5 µm diameter. This facility is capable of firing at a maximum shot rate of 1 shot every 30 – 40 minutes.

Bremsstrahlung photons and electrons are the primary radiations from ASTRA and VULCAN with an energy spectrum extending up to a few hundred MeV. Doses per shot at one metre from the targets are of the order of 10–100 mSv, depending on target type and Z, with an average energy less than 1 MeV.

Secondary radiations such as protons are produced with energy spectra extending to around 60 MeV. Yields are up to 10^{13} protons per shot with average energies of about 6 MeV.

3.1.10.1 Radiation monitoring at CLF

The monitoring programme for ambient radiation and contamination hazards follows the principle of "defence in depth" by using multiple measurement envelopes commencing at the source and extending to the exterior of the facility buildings. Active and passive methods are used. It should be noted that this programme is in addition to a monthly passive personnel dosimetry programme and routine surveys carried out by the Radiation Protection Supervisor. Experimental research is carried out to develop techniques for the detection of laser induced ionising radiation and optimisation of output.

Active monitoring is provided by scintillation detectors. Passive environmental radiation monitors, utilising CR39 and OSL TLD, are located inside facility target halls, in selected offices inside surrounding buildings and on the exterior of shielding. Passive monitors are analyzed monthly.

3.1.11 SRS (Synchrotron Radiation Source) at Daresbury

The Synchrotron Radiation Source at Daresbury uses high-energy electrons for the production of high-intensity radiation beams with wave lengths extending from infrared to hard X-rays for experiments across a diverse range of science disciplines. Techniques available include X-ray diffraction, X-ray spectroscopy (XAFS), small-angle/wide-angle scattering, soft X-ray spectroscopy, photoemission and imaging. Operating on a continuous basis it provides some 4500 hours of user beam per year to 30 experimental stations simultaneously, with an operating efficiency of about 90%. The SRS was commissioned in 1980 and is due to close at the end of 2008.

The facility comprises a suite of three electron accelerators, a 12 MeV linear accelerator and a 600 MeV booster synchrotron feeding sequentially into the third, which is the main storage ring operating at 2 GeV. The synchrotron light spectrum is emitted from dipole bending magnets and, enhanced in narrow spectral regions, from insertion devices. The SRS has five of these: two X-ray (high field superconducting) wigglers, a VUV-SXR undulator and three multipole wigglers.

The linac accelerates electron bunches with a peak current of 200 mA at 10 Hz for transfer to the booster synchrotron where the energy is increased to 600 MeV. The electron bunches are then injected into the storage ring until approximately 250 mA is accumulated. The injection system is then switched off and the energy of the electrons in the storage ring is then raised to 2 GeV.

The loss of high-energy electrons during the operation of these accelerators leads to significant fields of high-energy bremsstrahlung and neutron radiation.

3.1.11.1 Radiation monitoring at DL

A network of 31 installed radiation monitors has been implemented around the storage ring facility. These continually monitor the instantaneous radiation levels around the linac, booster, storage ring and experimental areas. Each beam line generally has one neutron monitor and one or more gamma monitors associated with it. All installed monitors undergo annual testing and calibration. The gamma monitors are type CGM5 manufactured to a Daresbury specification by Cooknell Electronics of Weymouth. The detection heads are ionization chambers type IG1 manufactured by Centronics filled to a pressure of 10 atmospheres of argon. The neutron monitor detection heads are TPA chambers manufactured by Centronics and filled to a pressure of 20 atmospheres of hydrogen. Again CGM5 control boxes are used.

3.1.12 CRC (The Cyclotron Research Centre) of the Université Catholique de Louvain

The CRC operates three different cyclotrons for use by national and foreign experimental groups. The one which produces also high-energy particles is the CYCLONE110 (CYClotron de LOuvain-la-NEuve). It is used for nuclear physics, isotope production and medical and technological applications. CYCLONE110 is a multi-particle, variable energy, isochronous cyclotron capable of accelerating protons up to 80 MeV, deuterons up to 55 MeV, alpha particles up to 110 MeV and heavier ions up to an energy of 110 Q^2/M MeV (where Q is the charge and M the mass of the ion). The energy range for heavy ions extends from 0.6 to 27.5 MeV/u depending, among other things, on the charge state of the ion. Other beams available include light and heavy ions (from gaseous and solid elements) and quasi-monoenergetic fast neutron beams in the 20 to 70 MeV range (see Section 6.3.1).

At the monoenergetic neutron beam line the maximum proton energy is 68 MeV with 10 µA on a 3 mm Li-target which produces 10^6 neutrons per second at 0°. The cyclotron frequency at this energy can vary between 13 and 20 MHz. The neutron spectra have been measured during calibration measurements of survey meters and personal dosimeters performed in collaboration with colleagues of PTB [(76)].

3.1.12.1 Radiation monitoring at CRC

At the neutron beam lines only neutron dose rate measurements are performed for area monitoring and radiation safety purposes, and ionization chambers are used for gammas. At other beam lines dosimetry is available by means of activation foils and alanine (Bruker e-scan).

3.1.13 DESY (Deutsches Elektronen-Synchrotron)

The German Electron Synchrotron DESY, member of the Helmholtz Association, is a national research centre supported by public funds and has locations in Hamburg and Zeuthen, Brandenburg. DESY performs basic research in the natural sciences with special emphasis upon:

– the development, construction and operation of accelerator facilities,
– particle physics (investigation of the fundamental properties of matter and forces),
– research with photons (investigations in all fields of natural sciences using synchrotron radiation).

Figure 23 shows the DESY accelerators. The Hadron-Electron Ring Accelerator HERA is a ring with 6.3 km circumference in which 920 GeV protons collide with 27.5 GeV electrons (or positrons). Before the electrons (red lines in Fig. 23) are injected in HERA they are pre-accelerated in the chain LINAC-II (to 0.45 GeV), DESY-II (to 8 GeV) and PETRA-II (to 12 GeV). The protons (blue lines in Fig. 23) come from LINAC-III (0.05 GeV), DESY-III (7.5 GeV) and PETRA-II (40 GeV).

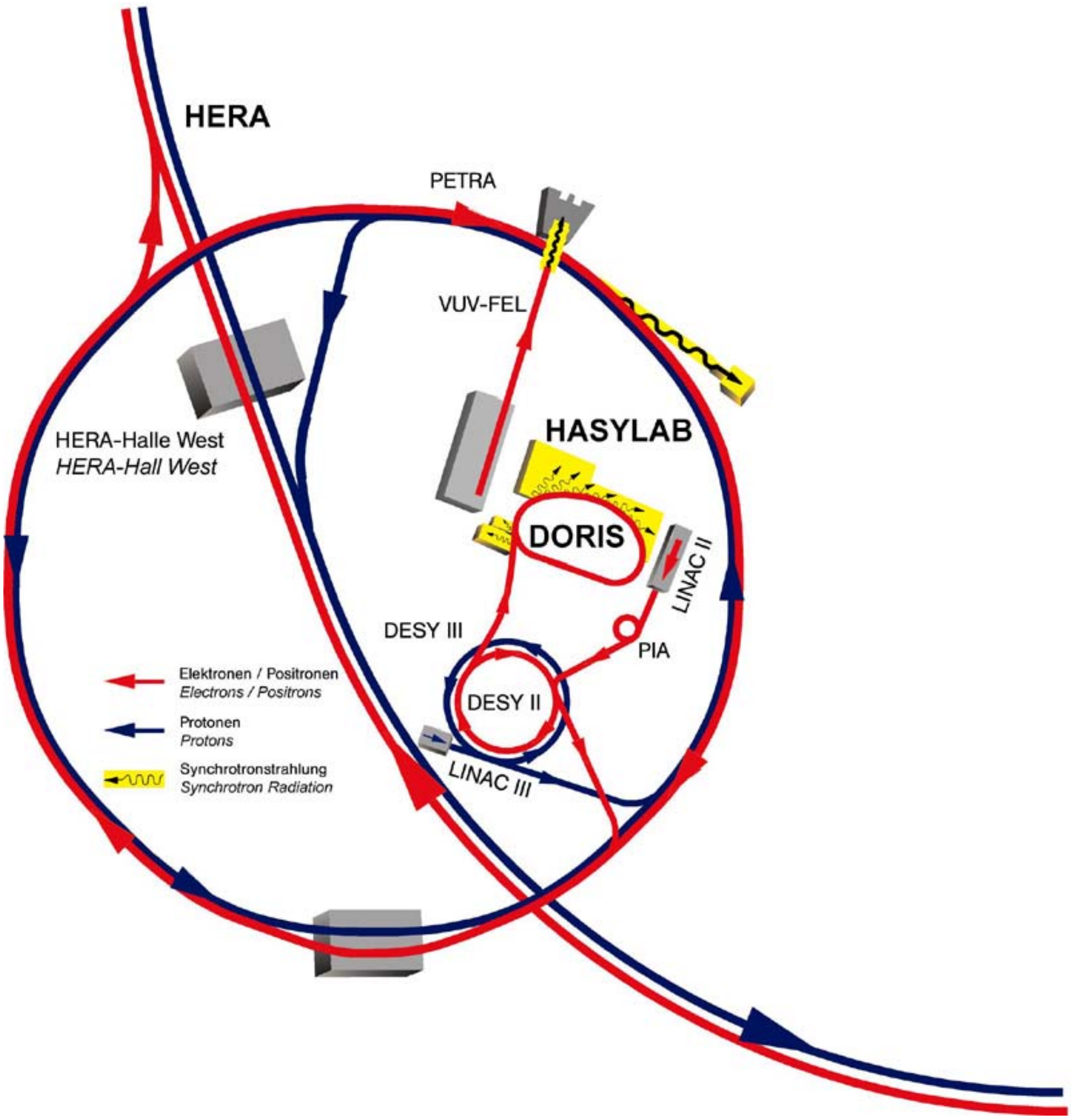

Fig. 23: Accelerators at DESY

The storage ring DORIS-III is a synchrotron radiation source with positron energy of 4.5 GeV. More than 20 beam lines guide the synchrotron radiation photons to the experimental stations. There is also one synchrotron radiation beam line at the PETRA-II ring, which is operated at 12 GeV between the HERA fills.

A new kind of synchrotron radiation source is being developed at DESY, the Free Electron Laser (FEL). The VUV-FEL, which started operation in summer 2005, is a linear electron accelerator at end energies in the range from 0.2 GeV up to 1 GeV with a very low duty cycle. Before being bent into the beam dump the electrons fly through a 30 m long undulator section where the laser light is generated with the wave lengths of the vacuum ultra violet (VUV) ranging from 100 nm down to 10 nm depending on the electron energy.

3.1.13.1 Radiation monitoring at DESY

Routine radiation monitoring at DESY is performed by means of passive and active dosimeters as listed in Table 5.

Table 5: DESY radiation monitors. The first column characterizes the type of dosimeter, the second column gives the kind of radiation the dosimeter is sensitive to, the third column lists the location at exposure time (employee means personnel dosimeter) and the fourth column gives exposure time and readout frequency.

Dosimeter	Sensitive to	Where	When
		Passive	
Photoluminescence	Electromagnetic radiation	Employee	All over the year, readout once per 2 months
CR – 39 Solid State Nuclear Track Detector	Low-energy neutrons	Employee	All over the year, readout once per 2 months
^{6}LiF/^{7}LiF thermoluminescence under PE moderator	Low-energy neutrons, electromagnetic radiation	Behind accelerator shielding	All over the year, readout once per month
Macrofol-foil in contact with a thin thorium layer	High-energy neutrons	Behind accelerator shielding	All over the year, readout once per month
Direct Ion Storage (DIS)	Electromagnetic radiation, synchrotron radiation	Outside optical hutches	All over the year, readout once per month
Cobalt sheet under PE moderator	neutrons	Inside accelerator tunnel, near beam lines	All over the year, readout once per year
		Active	
Rem counter BF_3 counter Under PE moderator	Low-energy neutrons	Behind accelerator shielding	All over the year, readout once per 10 seconds
Ion chamber 5 l Argon @ 10 bar	Electromagnetic radiation	Behind accelerator shielding	All over the year, readout once per 10 seconds
Proportional counter	γ radiation from residual activity	Inside accelerator tunnel, no beam	Measurement before maintenance, on request
NaI scintillation spectrometer	γ radiation from residual activity	At possibly activated accelerator components	Release procedure, on request
Proportional counter, low level counter	β radiation	Samples: water, soil, filter, dust	Once a year, on request

3.1.14 ESRF (European Synchrotron Radiation Facility)

The European Synchrotron Radiation Facility [(77)] located in Grenoble, France, is a joint facility supported and shared by 18 European countries. The ESRF operates the most powerful synchrotron radiation source in Europe (Fig. 24). Electrons emitted by an electron gun are first accelerated in a linear accelerator and then transmitted to a circular accelerator (booster synchrotron) where they are accelerated to 6 GeV. These high-energy electrons are then injected into a large storage ring, 844 m in circumference, where they circulate at a constant energy in a vacuum for many hours to produce high brilliance X-ray beams.

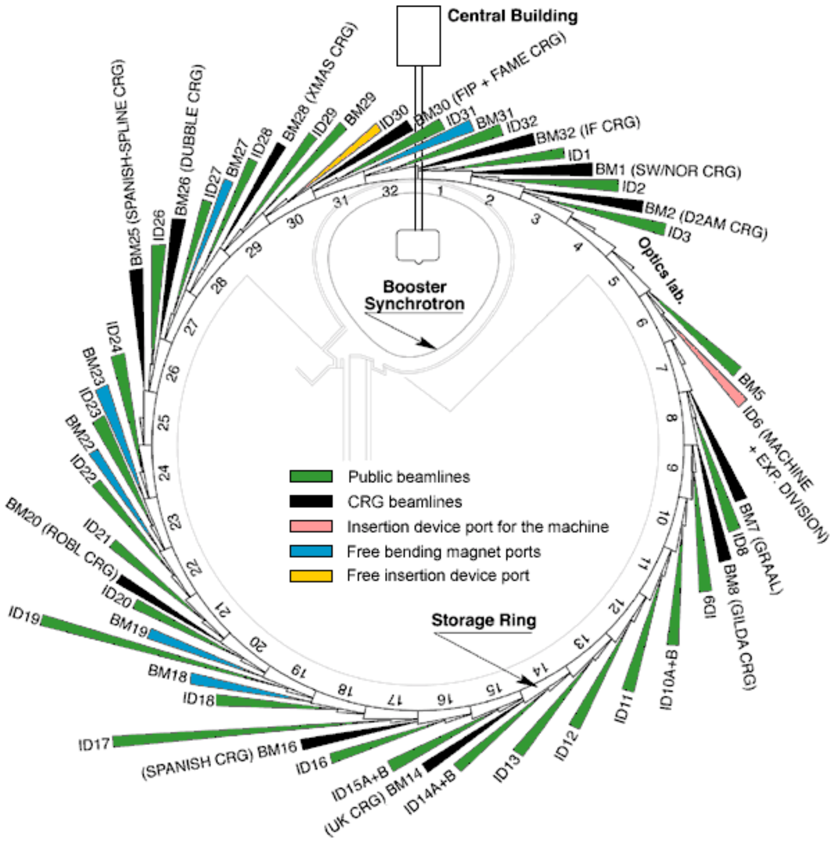

Fig. 24: Plan of ESRF experimental hall and beamlines

The facility operates during five experimental cycles per year, with an average duration of 8 weeks per cycle. After a start up period of 4 days, the facility runs continuously for beamline operation, interrupted every week by one day of operation dedicated to accelerator R&D studies. The standard ESRF filling pattern corresponds to a maximum stored current of 200 mA, with a beam lifetime of the order of 70 hours. Other filling patterns are used for time resolved experiments: 16-bunch mode and single bunch mode. Three types of beam losses occur: losses during injection, losses during stored beam decay and losses during (wanted or unwanted) beam dumps.

3.1.14.1 Radiation monitoring at ESRF

The radiation protection policy at ESRF stipulates that in all areas accessible during operation, radiation levels shall not exceed the legal radiation limits for non-exposed workers. Since electron losses, and the associated radiation levels around the storage ring, vary significantly from one moment to another, it was decided that dose constraints, enforced through interlocked radiation monitors, should be based on integrated dose rather than dose rates. On a longer time scale, dose levels will equally vary substantially from one day to another, with the highest doses occurring during machine start up and accelerator R&D studies. Finally, a large number of people, such as users and contractors, only stay at the ESRF for periods of the order of a few days or less, and it is therefore not sufficient to simply guarantee the respect of annual integrated dose limits. ESRF has therefore decided to implement a more stringent dose constraint, by continuously monitoring and limiting the integrated dose over 4-hours periods in all areas accessible during operation. From the 1 mSv annual legal dose limit [78] and the assumption of 2000 working hours per year, a dose constraint of 2 μSv integrated over 4-hour periods is derived.

This dose constraint is guaranteed through the implementation of an interlocked radiation monitoring system. These radiation monitors must meet stringent technical specifications, in particular they must be able to measure pulsed radiation with very low average dose rates, and have very good long term stability. The storage ring has a 32-fold symmetry. Radiation losses are distributed around the ring, in a typically non-uniform way. Indeed, highest losses will occur in a limited number of cells where the injection magnets and scrapers are installed. Loss levels in the other (standard) cells will depend on vertical limiting apertures and local vacuum levels. Within a unit cell the losses will essentially take place in the narrow gap of the insertion device vacuum vessels and in the achromats. Detailed shielding measurements have identified two locations per unit cell where the dose rates are highest within the cell. The interlocked radiation monitoring system is therefore based on two monitors per unit cell, or a total of 64 monitors for the storage ring. The results of the shielding measurements have also shown that neutron dose rates are about two times higher than photon dose rates. It was therefore decided to use neutron detectors as interlocked radiation monitors.

The relatively high energies of the neutrons and the requirement to measure integrated dose rather than dose rate have directed the choice to superheated drop neutron monitors [33, 34]. Sixty four active REMbrandt monitors, manufactured by Apfel Enterprises [32] are installed on the storage ring roof, distributed evenly along its 840 m circumference. While the REMbrandt monitors are no longer marketed, an upgraded version called ABC1260 (Framework Scientific, Newtown CT 06470 USA, http://www.framesci.com/) is now available [35]. All monitors installed at the ESRF use dichlorodifluoromethane emulsions (SDD-100^{TM}) supplied to ESRF by Yale University in the framework of a collaboration agreement.

These monitors are placed on the 1 m thick concrete tunnel roof. The roof provides slightly less shielding than the sidewalls, and by guaranteeing dose limits on the roof, these limits are therefore guarantee everywhere else around the storage ring. The neutrons measured outside the shield wall originate essentially from high-energy photo-spallation reactions, therefore neutrons with energies above 10 MeV account for a large part of the spectrum. The fluence response of the SDD-100 emulsions, compared to the ICRP74/ICRU57 fluence to ambient dose equivalent conversion factor [79], shows an increasing under-response for energies above 10 MeV [26]. This effect was initially taken into account at the ESRF in a conservative way, by multiplying by a factor of 2 the calibration factor of the vials obtained for a ^{252}Cf source. Currently the devices are being equipped with a 1 cm lead shell which was found to increase the response by 40% and thus render it accurate in high-energy fields.

3.1.15 BESSY (Berliner Elektronenspeichering Gesellschaft für Synchrotronstrahlung)

BESSY was founded in 1979 as a research institution dedicated to the production and provision of synchrotron radiation as a service for science and industry. BESSY operated the electron storage ring facility BESSY I from 1982 until the end of 1999. This facility located at Berlin – Wilmersdorf was Germany's first dedicated light source for vacuum ultra violet (VUV) and soft X-ray (XUV) radiation. The demand for a more powerful light source in the VUV and XUV range was the deciding factor which resulted in the construction of the new high brilliance synchrotron radiation source in Berlin – Adlershof. BESSY II, in operation since 1998, is a scientific centre located in an environment of university institutes, non-university research organizations and technology-oriented enterprises.

BESSY II (Fig. 25) consists of a 50 MeV microtron, a full energy synchrotron and a 1.9 GeV storage ring. The circumference of the synchrotron is 96 m and of the storage ring 240 m. The injection elements are operated at a rate of 10 Hz. The storage ring is operated on three shifts, with 3 to 5 injections per day. Besides section 1 (injection) and section 16 (RF), every straight section houses insertion devices. Among them there are four superconducting wigglers, providing hard X-rays for various experiments and X-ray lithography.

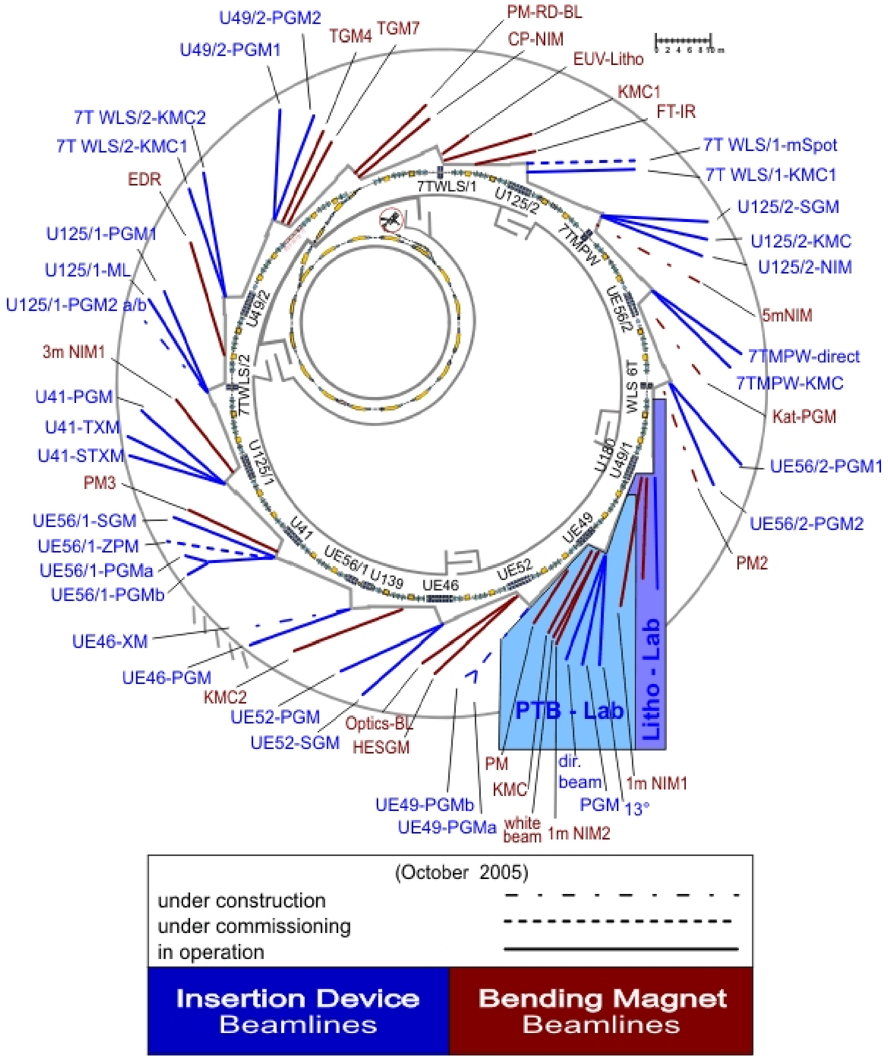

Fig. 25: BESSY machine components and beamlines

BESSY is involved in the planning, and beginning in July 2006, in the commissioning of the Metrology Light Source (MLS) of the Physikalisch Technische Bundesanstalt (PTB), that is currently under construction close to the BESSY site. BESSY plans also a HGHG – FEL project with 2.3 GeV and 150 kW DC beam power. Such facility will produce coherent flashes of photons with wavelengths of a few nanometres, extreme brilliance (higher by 10 orders of magnitude compared to 3rd generation light sources) and femtosecond pulse duration.

3.1.15.1 Radiation monitoring at BESSY

The technical requirements of the monitoring instrumentation are largely defined by the injection mode. The injections last one to two minutes, the synchrotron pulses have a length of 300 ns, the repetition rate is 10 Hz. BESSY uses a network of active measurement stations consisting of ionization chambers (35 keV–7 MeV, 10 nSv/h–10 Sv/h) and BF_3 neutron counters (0.025 eV–15 MeV, 0.4 Sv/h) by Thermo Electron Corporation, Erlangen, Germany. The dose rates are accumulated by a portable computer every minute. The measurement stations around the storage ring are located outside the tunnel at places with the lowest transversal distance to the machine. Losses by dead time effects due to the pulsed radiation are less than 1% at normal injections and less than 10% at crash conditions during injections. Between injections the dose rates are close to the natural background at most places outside the shielding wall. Thermoluminescent dosimeters (LiF) placed at several locations outside and inside the tunnels are also used.

The slower the repetition rate and the shorter the pulses, the bigger are the dead time effects. This problem can occur at stochastic beam dumps and even more at the so called top-up operation, where injections are conducted with open beam shutters at repetition times of e.g. 30 s. Another still unsolved problem is the availability of active neutron detectors, which can measure high energy neutrons up to 200 MeV. The energy spectrum of neutrons at BESSY was calculated with the FLUKA Monte Carlo code. From that it is estimated that the dose due to neutrons with energy larger than 10 MeV is approximately the same as from the lower part of the neutron spectrum (energy below 10 MeV).

3.2 Medical hadron accelerators

This section briefly describes the European medical facilities involved with cancer therapy with hadron beams (see, for example, ref. [(80)]), and the related radiation monitoring. This section only focuses on accelerators capable of delivering beams, either protons or light ions, with energy sufficient for the treatment of deep seated tumours. This requirement fixes the minimum energy for protons at about 200 MeV: proton accelerators delivering 60 to 70 MeV protons for the treatment of eye tumours only are thus not included in this review. At present there are only a limited number of facilities of this type in operation or under construction in Europe: these are ICPO in France, PSI in Switzerland, HIT in Germany, CNAO in Italy and RPTC in Germany. For completeness the facilities at JINR in Dubna are also included. Two other projects have been funded: ETOILE in Lyon (France) and ATREP in Trento (Italy), but they are still at the planning stage and have not yet selected the type of accelerator (cyclotron or synchrotron). Med-Austron in Austria is on its way to secure funding. TSL, Uppsala, Sweden performs proton therapy on a routine bases, as has been discussed in Section 3.1.4.

3.2.1 Institut Curie - Centre de Proton thérapie d'Orsay (ICPO)

The Institut Curie – Centre de Protonthérapie d'Orsay (ICPO) is one of the two French institutes for medical treatment using proton beams (Fig. 26). The centre was created in 1991 and up to now more than 3000 European patients have been treated. Ophthalmic and cranium tumours are treated in two separated rooms where the proton beam is respectively sent at maximum energy of 73 MeV and 200 MeV.

Protons are produced by a synchrocyclotron delivering a pulsed beam with frequency of 448 Hz and a proton pulse length of 20 µs. To lower the maximal energy of 200 MeV, a graphite moderator is inserted inside the beam line upstream of the bending magnet. The intensity of the proton beam is measured with an ionization chamber upstream of the optical beam line. This ionization chamber of type "Neptune" is commercialized by General Electric. A second chamber that is used as dose monitor is placed downstream of the proton beam.

Neutron area monitoring is performed with active and passive devices. The active neutron monitor, called BEFIC A 003, consists of a cylindrical proportional counter filled with ^{3}He gas used with a moderator polyethylene sphere. This monitor is yearly calibrated with an AmBe source owned by the radiation protection department of IPNO (Institut de Physique Nucléaire d'Orsay). Neutron area monitoring is also performed with passive dosimeters based on CR39 foils. These dosimeters are placed on the walls around the controlled area and are read monthly by the IPNO radiation protection department. The CR39 is calibrated with an AmBe source at IPNO. For photons, area monitoring is performed with active survey-meters from Saphymo, calibrated once per year with a Co gamma source at IPNO.

Monte Carlo simulations of the facility were undertaken to improve the knowledge of the secondary radiations in the treatment areas.

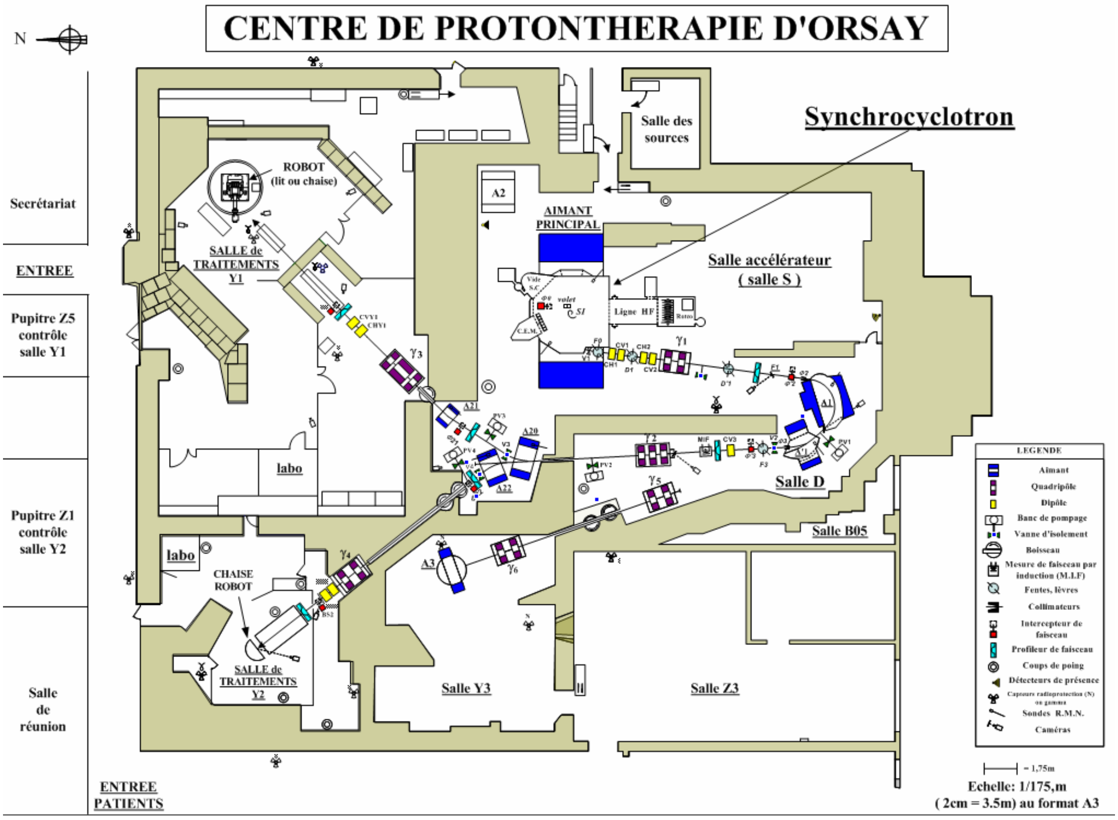

Fig. 26: Centre de Proton thérapie d'Orsay. The treatment rooms are called Y1 and Y2

3.2.2 Joint Institute for Nuclear Research, Dubna, Russian Federation

The JINR has six partly independent laboratories. Four of them run high-energy accelerators. Two laboratories, described in this section, perform radiation therapy with hadron beams.

3.2.2.1 The Dzhelepov Laboratory of Nuclear Problems (DLNP)

Clinical proton therapy started at Dubna in 1967 but it was interrupted between 1974 and 1987, when the previous synchrocyclotron was reconstructed to the actual phasotron facility (Fig. 27). The basic characteristics of the beams available at the phasotron of the Dzhelepov Laboratory of Nuclear Problems (DLNP) [(81)] are given in Table 6.

Table 6: Beams available at the phasotron of DLNP, Dubna

Energy of accelerated protons	(659 ± 6) MeV
Energy dispersion	(3.1 ± 0.8) MeV
Frequency of acceleration	250 Hz
Ejected [a)] beam intensity (fast mode, pulse duration 30 μs)	(2–2.5) μA
Ejected [a)] beam intensity (slow mode, beam within 85% of modulation period with 4 ms duration	(1.6–2.0) μA

[a)] The extracted beam has a micro-structure: particle bunches of 10 ns duration spaced by an interval of about 70 ns.

In the first period 84 patients were treated. The reconstruction was completed by the end of 1985. A six-room medical facility at the JINR Laboratory of Nuclear Problems includes:

- four medical beam lines intended for irradiation of deep seated tumours with broad and narrow proton beams of various energies (between 100 and 660 MeV),
- a medical pion channel for beam therapy using high-intensity negative pion beams with energies between 30 and 80 MeV,
- a neutron channel for medical purposes (the average energy of neutrons in the beam is approximately 350 MeV) for irradiation of large radio-resistant tumours.

Up to now, only proton beams have been used. The total number of patients treated at the JINR is 442 up to July 2005. Typical dose rates are of the order of several Gy per minute.

Since 2001 great importance has been given to three-dimensional proton conformal radiation therapy and radiosurgery, to decrease normal-tissue integral dose significantly while achieving a highly conformal dose distribution in the target area. This is especially advantageous for many critically located and complex-shaped intracranial tumours and arteriovenous malformations (AVM).

In 2004 a new proton beam with average energy of 225 MeV was extracted to treat particularly prostate cancer and other deeply located targets. The ridge filter system permits to form a depth-dose distribution with Spread-Out-Bragg Peak (SOBP) with width of about 70–85 mm in water. Beam dosimetry and monitoring is assured with ionization chambers, silicon and diamond detectors. All dosimetric data were used to develop the technique of 3D conformal proton radiation therapy and its treatment planning.

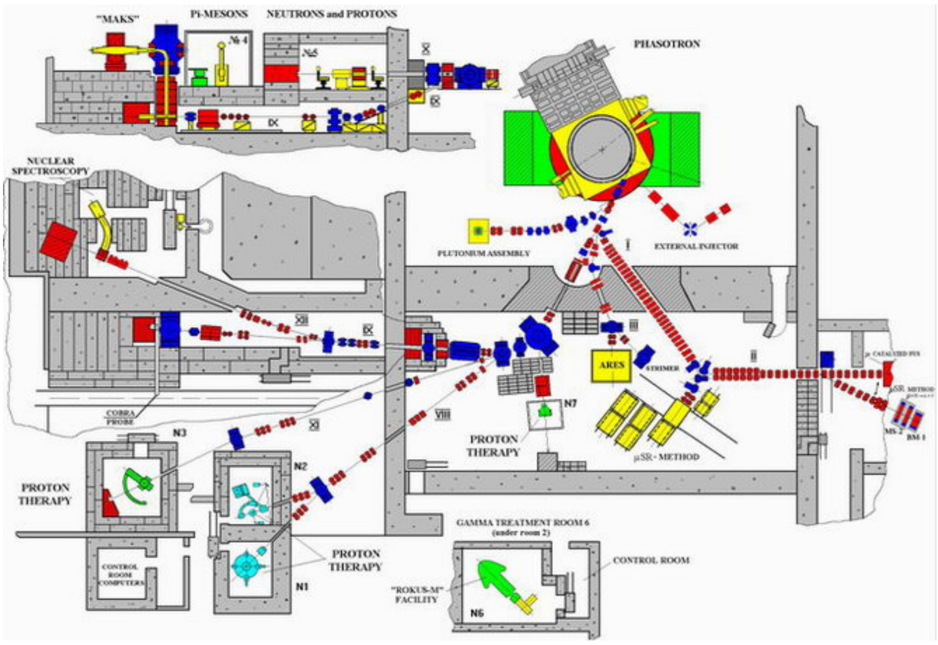

Fig. 27: Layout of the JINR phasotron and its beam lines after the planned upgrade

3.2.2.2 The nuclotron of the Veksler and Baldin Laboratory of High Energies (VBLHE)

The nuclotron of the VBLHE (81) is able to accelerate particles with $Z \leq 26$, up to 3 GeV/u. Since 2004, attempts have been started to produce ^{12}C ion beam for hadron therapy, with the nominal energy of about 500 MeV/u. No clinical tests have been performed up to now.

3.2.2.3 Radiation protection

There is another Laboratory of the JINR Dubna with high-energy charged particle accelerators: the Flerov Laboratory of Nuclear Reactions with cyclotrons U400, U400M and IC100 (81).

Radiation protection at the JINR Dubna as a whole is assured for neutrons by means of sets of moderator-type area monitors. This monitor, of Russian production, is basically a 10 inch sphere with a BF_3 counter and a Cd internal layer. The data from all monitors are registered in a station, separately for each of the Laboratories mentioned above. The area monitoring for photons is assured by means of GM counter based equipment of Russian production. Automatic registration of photon monitor data is not regularly performed.

Radiation protection measurements in mixed radiation fields have been performed using recombination chambers, both in accessible areas (82) and inside the treatment room for proton therapy (83). Photon individual dosimetry is performed by means of TLDs (LiF). Nuclear emulsions are still used for individual neutron dosimetry. However, due to the end of their production in Russia, a new solution is on the way to be decided. The most probable will be an albedo-system with ^{6}LiF / ^{7}LiF detectors.

3.2.3 PROSCAN at PSI

In addition to physics research, PSI is also involved in Life Sciences, focusing on cancer therapy by particle beams. In this context PSI, as a world pioneer, developed two proton therapy facilities. In 1984 the Ophthalmologic Proton Therapy Installation Switzerland (OPTIS) was started. It utilizes 72 MeV protons generated by the original injector cyclotron. Up to February 2005 more than 4200 patients have been treated. The Gantry I device for spot-scanning-technique, also developed at PSI and located in the NA-hall, was commissioned in 2001. It uses a small fraction of the splitted high-energy proton beam. Until the end of 2004 209 patients have been treated with the 590 MeV proton based facility.

In 2001 PSI decided to start the spot-scanning-technique development programme PROSCAN (Fig. 28), in order to realize a proton therapy facility appropriate for the commercial use of radiation therapy in hospitals. The facility is presently in the commissioning phase and will be ready for patient treatment during 2006. The protons, having extraction energy of 250 MeV and beam intensity between 1 nA and 500 nA, are generated by a 250 MeV superconducting compact cyclotron with a high extraction efficiency of 0.8. Energy tuning between the nominal energy and about 70 MeV will be performed by a multi-wedge graphite degrader. In a first step the therapy beam will be guided onto the existing Gantry I. It is also foreseen to install an improved gantry (Gantry II) during 2006.

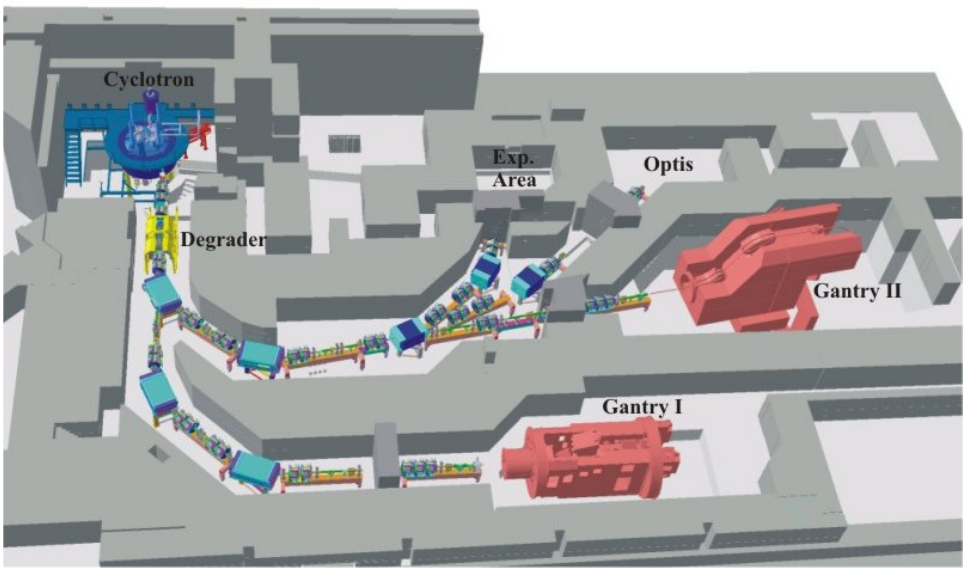

Fig. 28: 3D-view of the PROSCAN medical accelerator facility at PSI (shielding ceiling partly removed)

3.2.4 Heidelberg Treatment Facility (HIT)

The Heidelberg Heavy Ion Therapy (HIT) facility (Fig. 29) is dedicated to tumour treatments with carbon beams, but also treatments with protons, ^{3}He and oxygen ions are planned. The facility will have two horizontal treatment rooms and one room equipped with a gantry delivering carbon beams (or other ion beams), a facility presently unique worldwide. In all treatment rooms the raster scan method is applied. The raster scan is an active method where the whole tumour can be scanned by variation of the beam energy and by the beam position via deflection magnets. The accelerator facility comprises two ion sources, a synchrotron and a linac as an injector for the synchrotron which consists of a RFQ and an IH structure. The beam parameters are: energy range from 50 MeV/u to 430 MeV/u, the maximum number of ions per spill is from 4×10^{10} for protons to 5×10^{8} for oxygen (which can be reduced up to a factor of 10^{3} lower), the beam spills have a microstructure which results in fluctuations in the µsec and 1/10 µs ranges.

The facility is planned to treat about 1000 patients per year. The accelerators, which are built by the accelerator department of GSI, will begin operation in 2006 and patient treatments are due to start by the end of 2007. The facility is situated in the vicinity of the Heidelberg university hospital 'Kopfklinik'.

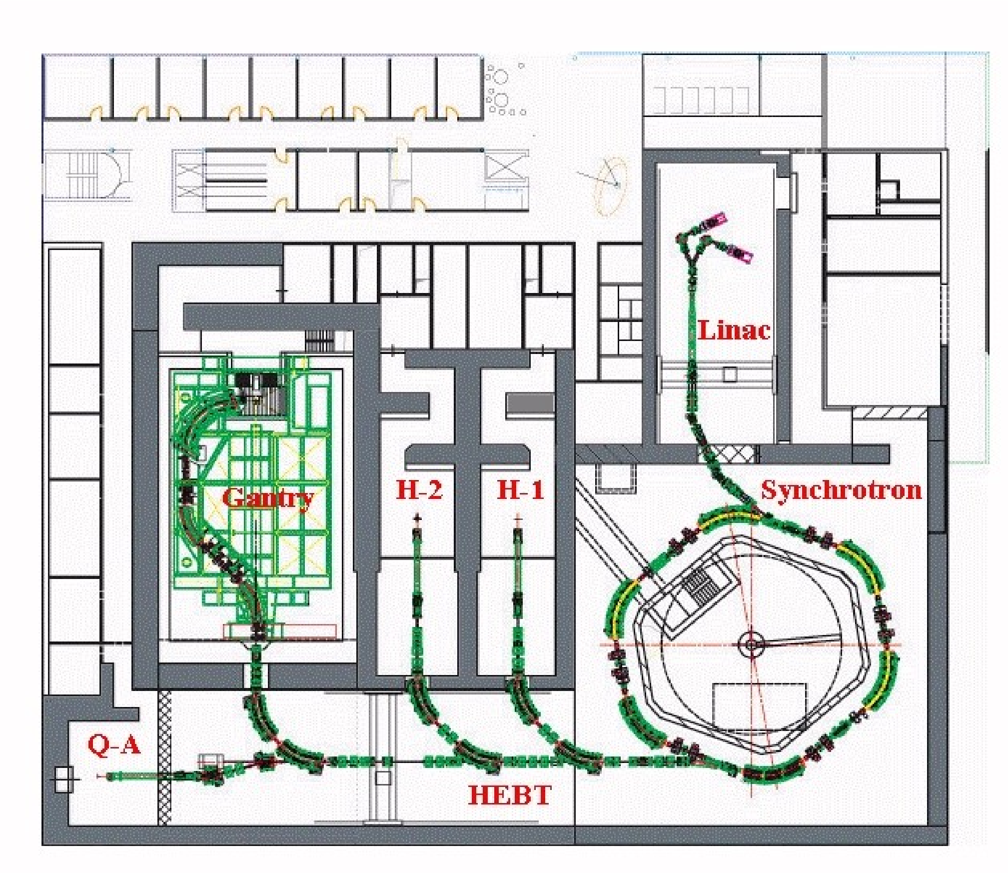

Fig. **29**: The Heidelberg heavy-ion facility for tumour irradiations with protons, He, C and O ions in three treatment rooms. One room is equipped with a gantry and all use the active raster scan method for beam delivery.

3.2.4.1 Planned radiation monitoring for HIT

The HIT facility is presently under construction and the tendering procedure for the radiation monitoring systems is under way. Both neutron and gamma detectors will be used for area monitoring. For neutrons use will be made of rem counters suitable to measure also high-energy neutrons in the range up to about 1 GeV. The facility will also be equipped with dose rate meters for the measurement of activated structures and components. The use of passive dosimeters for neutron radiation detection is also planned. Compliance with the annual dose limits — given by the German radiation protection ordinance — will also be assured by area monitoring with polyethylene spheres provided with an additional lead layer to measure high-energy neutrons, in combination with $^{6}Li/^{7}Li$ TLDs.

3.2.5 Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia

The Centro Nazionale di Adroterapia Oncologica (CNAO, National Centre for Oncological Hadrontherapy) (Fig. 30) will be the first hospital-based facility in Italy for the treatment of deep seated tumours with hadron beams. The centre is presently under construction in Pavia on a 37000 m^2 site located next to the highway, to the university and to three hospitals. The CNAO has been conceived to treat deep seated tumours with ion beams with Z in the range 1 to 6. Operation will start with protons and carbon ions, but the possibility to add other species is left open. Its core accelerator is a synchrotron with a circumference of 78 m capable of accelerating carbon ions up to 400 MeV/u kinetic energy and protons up to 250 MeV, with maximum beam intensity of 4×10^8 ions/spill and 10^{10} protons/spill, respectively. The beam is slow-extracted with spill duration variable between 1 s and 10 s. The beam is delivered to three treatment rooms, one equipped with a vertical and a horizontal beam line and the other two with a fixed horizontal line. Space for the future upgrade of the centre with two additional rooms equipped with gantries is available and the synchrotron has been designed to work with these two additional lines. Treatments are expected to start at the end of 2007. The injection chain is made of a 8 keV/u Low Energy Beam Transfer line (LEBT), a RFQ accelerating the beam to 400 keV/u, a linac to reach the injection energy of 7 MeV/u and a Medium Energy Beam Transfer line (MEBT) to transport the beam to the synchrotron.

The dose delivery system is completely active as it allows the best conformation of the dose to the tumour volume, avoiding the need of moderators and collimators. Since the unit volumes into which the pencil beam deposits its Bragg peak, commonly referred to as “volume pixels” or “voxels”, are small each of them is treated in a short time. This requires special care in the slow extraction process in order to have a spill as uniform as possible. CNAO will use a “betatron core” magnet to drive the extraction process. This is a cylindrical magnet in which the beam passes along the cylinder axis. The magnetic field encompasses the beam and when the magnet is excited the flux variation slightly accelerates the particles driving them into the extraction resonance.

The LEBT lines bring the beam from the sources to the RFQ. Two ECR sources are kept in operation at the same time to allow maximum current stability and fast switching between ion species. The presence of one spectrometer per source allows beam optimization on one line while the other one is in use. The ion specie can be changed within few seconds by just changing the magnet settings. The beam energy in these lines is 8 keV/u for both $^{12}C^{4+}$ and H_2^{+}.

The RFQ – Linac system is identical to the one designed by GSI for the Heidelberg facility discussed in Section 3.2.4. It accelerates particles with $A/Q < 3$ and initial energy of 8 keV/u to 7 MeV/u. The Linac structure is of the IH-DTL type with a RF frequency of 217 MHz. The total length of the RFQ-Linac section up to the stripping foil is less than 7 m.

The MEBT transports the beam from the stripping foil to the injection point in the synchrotron. In the MEBT a final selection of ion specie is made to avoid beam contamination with particles that before stripping have the same A/Q as the desired one.

The HEBT lines transport the beam extracted from the synchrotron to the three treatment rooms. All lines are equipped with a pair of scanning magnets which allow scanning over an area of 200 mm × 200 mm.

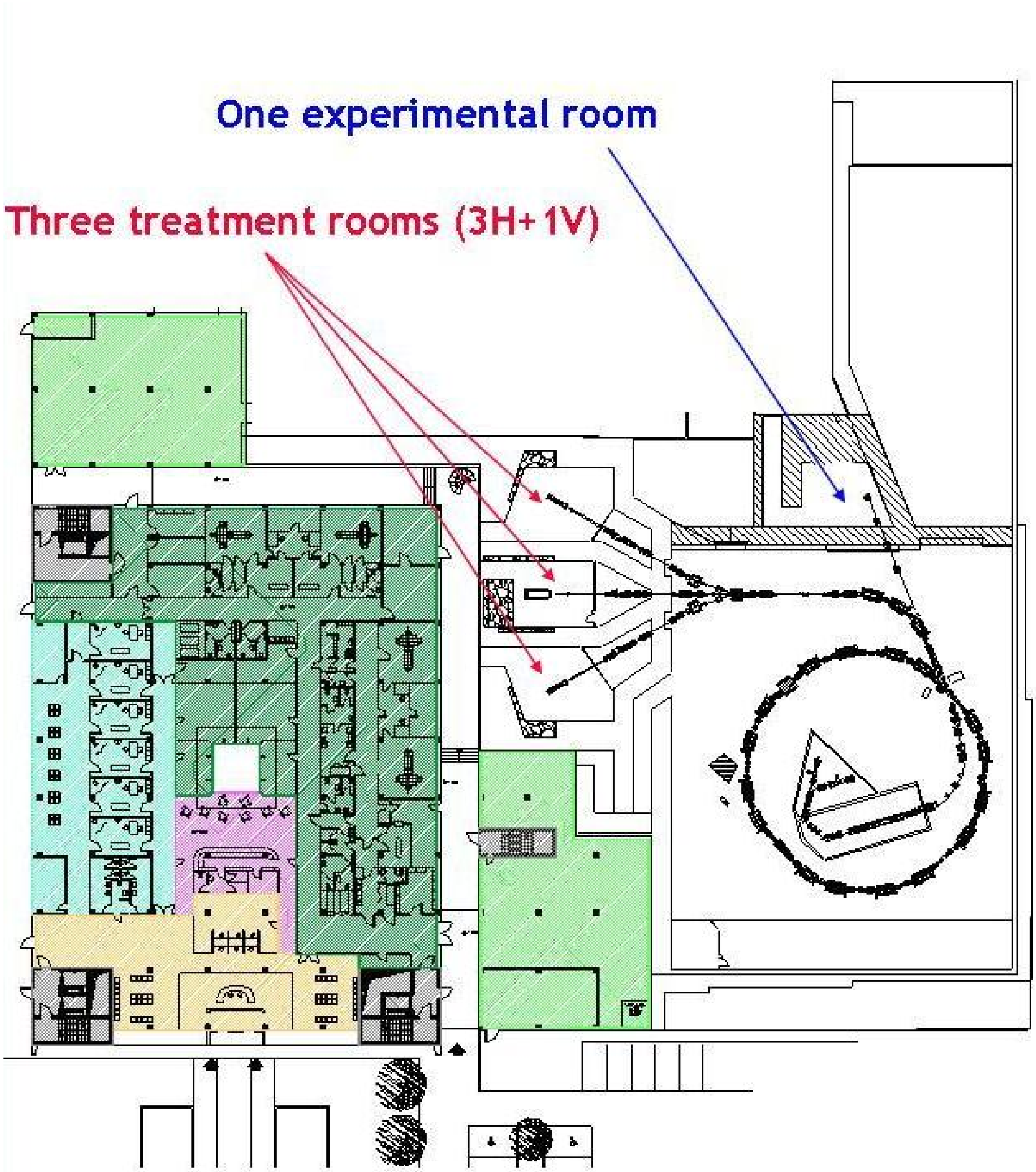

Fig. 30: Plan view of the main floor of the Centro Nazionale di Adroterapia Oncologica in Pavia showing the accelerators, the three treatment rooms, the central one equipped with one horizontal and one vertical beam, the other two with one horizontal beam. On the upper part space is available for two gantry rooms planned for a future upgrade.

3.2.5.1 Planned radiation monitoring at CNAO

The facility is under construction and the procedures for the tender for the radiation monitoring system are in progress. Area monitoring will be based on 1) passive dosimetry (^{6}LiF/^{7}LiF TLDs) under a polyethylene moderator and CR39 based dosimeters, 2) active dosimetry (conventional rem counters, extended range rem counters and high pressure ionization chamber), and 3) on-line monitoring using ionization chambers and conventional as well as extended rem counters.

For the measurements of activated structures and components, the facility will be equipped with ambient dose equivalent rate meters as well as gamma spectrometry systems based on high-purity germanium and/or NaI detectors.

3.2.6 Rinecker Proton Therapy Center (RPTC)

The Rinecker Proton Therapy Center (RPTC) in Munich is a European proton radiation centre for outpatient treatment of tumours, providing a complete hospital setting [(84)]. The RPTC has been designed for the treatment of 4,000 to 5,000 patients per year. The centre is equipped with five treatment rooms, four provided with isocentric gantries and one with a fixed horizontal beam line (Fig. 31). The four gantries are operated with an active 3D pencil beam scanning system, which allows field sizes of up to 30×40 cm^2 at the full energy range from 70 to 250 MeV.

The protons are accelerated in a superconducting cyclotron to 250 MeV. The cyclotron has an extraction efficiency of 80% and the extracted proton beam current is variable up to 1 µA. During the clinical usage or upon an emergency condition the beam can be stopped very fast, with a switch off time of the order of 50 µs. In order to reduce the radiation level the beam is dumped at low-energy (below 10 MeV).

The fixed extraction energy is degraded to the required clinical entrance energy (according to the treatment depth) in an energy selection system (ESS) located downstream of the cyclotron. The ESS consists of a multi-wedge graphite degrader and an achromatic spectrometer (two 65° dipole magnets, variable slits system, etc.). From there on the proton beam is delivered to any of the five treatment rooms without any further particle loss. A typical beam current used for patient treatment is in the order of 1 nA.

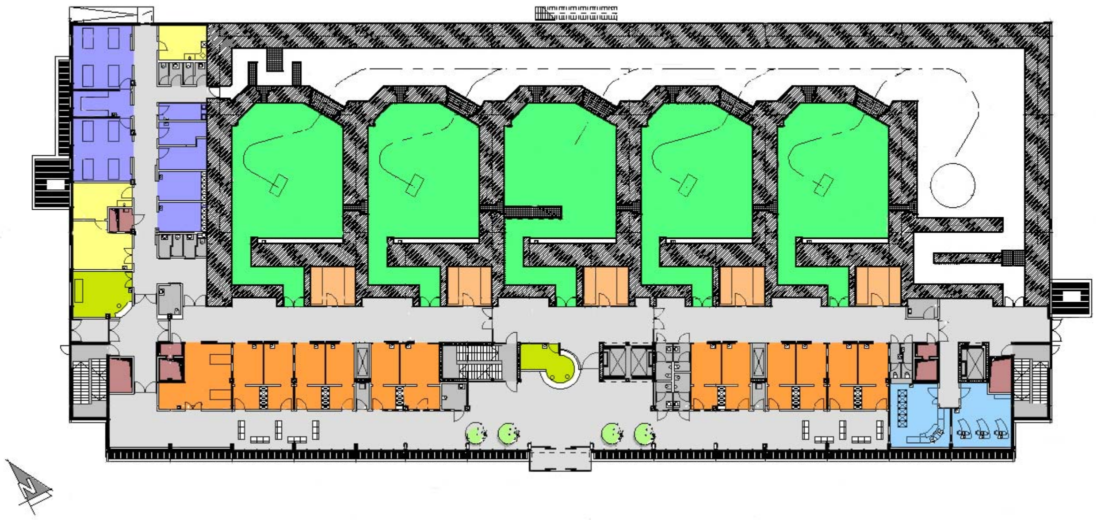

Fig. 31: View of the ground floor of the RPTC

3.2.6.1 Radiation protection at RPTC

Various neutron and γ dose measurements and a surveillance of possible activation in the environment of the facility are carried out. These measurements of e.g. neutron and γ dose inside and outside the building are performed with TLDs. Monitoring of the exhaust air and ground water with respect to activation is carried out on a regular basis. All of these measurements are performed with commercial detectors and equipment.

To ensure the beam quality for patient treatments several different detectors for beam monitoring and dose rate measurements can be inserted in the beam line. All these detectors are retractable from the beam path. Directly in front of the patient two dose monitors and a multi-strip ionization chamber (for beam positioning) are located inside the nozzle. These detectors are especially developed for this purpose by the manufacturer to ensure a fast beam dose delivery control.

4 Radiation protection and monitoring at European thermonuclear fusion facilities

Many radiation protection issues at experimental thermonuclear fusion machines and at associated facilities are similar to those arising around medium and low-energy accelerators. Radiation fields around these facilities are complex and mainly composed of neutrons and photons. Pulsed fields, short operation periods, complex operation scenarios, variable radiation energy spectrum are common situations at nuclear fusion facilities. The main difference to the radiation fields described in Section 3 is the lower maximum neutron energy: about 2.5 MeV for D-D plasmas and 14 MeV for D-T plasmas.

A specific radiation monitoring problem arises at fusion facilities related to the short time during which the so called ‘plasma burning’ (or ‘shot’ or ‘pulse’) takes place. In this time period, that ranges from about 1 second to some tenths of seconds, plasma heating systems are activated and the thermonuclear conditions make it possible the fusion reactions. Usually an intense, mixed neutron/photon radiation field is generated during the burning phase and to collect the needed dosimetric information the monitoring response during this interval has to be recorded. This is usually accomplished with active monitors and associated electronic devices suitable to activate the measurement for the time needed and to record the related dosimetric information.

4.1 Joint European Torus (JET)

The JET machine, its sub-systems and buildings were designed and constructed for safe operation with tritium and the associated high neutron and gamma yields. The machine operates in a pulsed mode. Pulses can be produced at a maximum rate of about one every twenty minutes, and each one can last for up to 60 seconds in duration. An extensive set of radiation monitoring equipment for gamma and neutron emissions as well as tritium has been installed in and around the main torus hall (J1T). There is also tritium monitoring in the Active Gas Handling Building (J25) and the Waste Handling Facility (J30). A comprehensive environmental monitoring programme completes the radiation protection measurements.

4.1.1 Gamma and neutron radiation monitoring at JET

There is a variety of radiation monitoring equipment on the JET site, which include portable and fixed monitors. Fixed gamma and neutron monitors for the working areas are on line to the JET computer system, CODAS. There is also a large set of passive dosimeters (TLDs for gammas and ^{237}Np with a polycarbonate film for neutrons) deployed around the J1 building, particularly at penetrations through the biological shield and known scatter paths. High and medium level neutron and gamma monitors are used around the JET facility.

High level neutron (HLN) monitors are required in the torus hall to measure neutron doses during machine pulses. The neutrons are thermalised by polythene cylinders surrounding ionization chambers filled with a gas which makes them sensitive to thermal neutrons. This method has the disadvantage that such an instrument has an appreciable gamma ray response. Other methods, such as BF_3 proportional counters, will not cope with the high dose rate during a JET pulse.

Medium level neutron (MLN) monitors are required to measure the neutron dose during a pulse. The dose equivalent per pulse may vary from 40 nSv to 6 µSv depending on monitor location. This is a small fraction of the total dose equivalent in these areas. The neutrons are thermalised by a polythene cylinder and detected by a BF_3 proportional counter. This system has a very good gamma ray rejection.

High level gamma ray (HLG) monitors are required to measure a wide range of dose equivalent rates. A D-T pulse of 10^{20} neutrons could produce a dose equivalent of 20 Sv. The total dose to the monitors over the life of JET may be up to 0.5 MGy. These monitors are also used to measure dose rates from activated equipment. Ionization chambers are used as the preferred method of detection, with a few minor modifications.

Medium level gamma ray monitors are required in areas close to the torus hall in order to measure gamma ray dose during machine pulses and the background dose rates in the area. They will also measure the gamma dose rate due to any release of gamma emitting or positron emitting radionuclides into the workplace atmosphere. The instruments are required to measure radiation from background levels of 0.1 µSv/h to about 3 mSv/h. Compensated Geiger Müller counters are used as the method of detection.

Signal pulses from the active monitors, proportional to the dose rate, are sent to a suitable interface with a CAMAC (Computer Automated Measurement And Control) system scaler at a central cubicle. The detector head and associated electronics are separate units so that the head can be placed in the torus hall and the electronics placed in a lower dose environment in the CAMAC cubicle area. The instruments are read, through the CAMAC interface, by the CODAS computer system. The monitors send pulses to CAMAC scalers which are read at intervals of 5 minutes and additionally before, during and after each pulse using a serial highway connection. Software is provided to display the readings on these monitors and to provide archiving of data. The instruments are self testing having a small built in gamma ray check source (0.5 µSv/h) to guarantee a low counting rate when in normal operation. Current dose rates from all active monitors are available on screens in the control room.

In the neptunium fission method used for routine passive neutron dosimetry, fission fragments from a ^{237}Np foil produce damage tracks in a thin polycarbonate film held against it. These damage tracks are subsequently etched into holes by the action of caustic alkali (potassium hydroxide) solution. They are then counted by placing the polycarbonate film between a solid conducting electrode and an aluminised plastic foil and applying a high voltage (spark counting system). The dosimeter consists of a plastic case with a ringed lid, in which two lead shields and an aluminium holder containing a neptunium foil are fixed. The case is marked externally with the number of the foil it contains and has the word FRONT embossed on its lid. One lead shield (1 mm thick) is glued to the inside of the lid and the other (3 mm thick) is glued into the base of the dosimeter (underneath the foil holder). A thin layer of ^{237}Np (0.5 mg/m^2) coated on a 30 mm × 30 mm square aluminium backing foil (0.25 mm thick) is sealed behind a 2 µm aluminised polycarbonate window in the aluminium holder. The track detector (or film) is a 30 mm × 30 mm square film of 10 µm polycarbonate which is held in a numbered rectangular frame for ease of handling. These dosimeters are normally replaced every four weeks.

Passive thermoluminescent dosimeters (TLD), neutron-insensitive, are used to determine the doses due to both penetrating radiation, such as X-rays and gamma rays, and less penetrating radiation, such as beta particles. They are not sensitive to alpha particle radiation. TLDs issued at JET are not used to determine neutron doses. If it is necessary to measure neutron doses, use is made of additional passive devices, either neutron track plates or dosimeters incorporating a CR39 plastic.

The doses accrued by the environmental dosimeters are measured on the same reader used in the personnel dosimetry service. These dosimeters are normally replaced every four weeks.

4.2 Nuclear fusion activities at the ENEA Frascati Research Centre

The ENEA research centre situated in Frascati, Italy, is mainly devoted to studies, research and developments in the field of the nuclear fusion applications. An experimental thermonuclear fusion machine (FTU) is in operation at the Frascati Centre together with some other associated facilities among which a neutron generator (FNG) is the main one.

FTU is a compact, high magnetic field tokamak. It began operation with plasma in 1990, and it is still producing good physics results. It has achieved its design parameters: 1.6 MA at 8 T, and plasma density larger than 3×10^{20} m^{-3}. FTU is provided with three additional heating systems (LH, ECRH and IBW), two pellet injection systems, one shooting along the major radius and one shooting along a vertical chord in the high field region and of course a complete set of plasma diagnostics. Higher neutron intensity around the tokamak is less than 10^{14} n/s due to fusion D-D reactions and to electron runaway effect. The energy spectrum of the D-D neutrons produced at FTU is shown in Fig. 32 (85).

The 14-MeV Frascati neutron generator (FNG) is a neutron generator based on the T(d,n)α fusion reaction designed and built at ENEA Frascati; FNG produces up to 10^{11} neutrons per second in steady state or pulsed mode. The energy spectrum of the D-T neutrons produced at FNG is shown in Fig. 33 (85). FNG can also produce 2.5 MeV neutron via the D(d,n)^{3}He fusion reaction. FNG was designed for conducting neutronics experiments in the framework of the research activity on controlled thermonuclear fusion. The neutronics design of blanket and shields of the next-step fusion devices requires verification that the neutron cross section data used in the calculations are as accurate as possible and confirmation that the calculation tools used to transport the neutrons are as reliable as practical. To ensure that these criteria are met, a suitable experimental activity (benchmark experiments) is carried out using FNG.

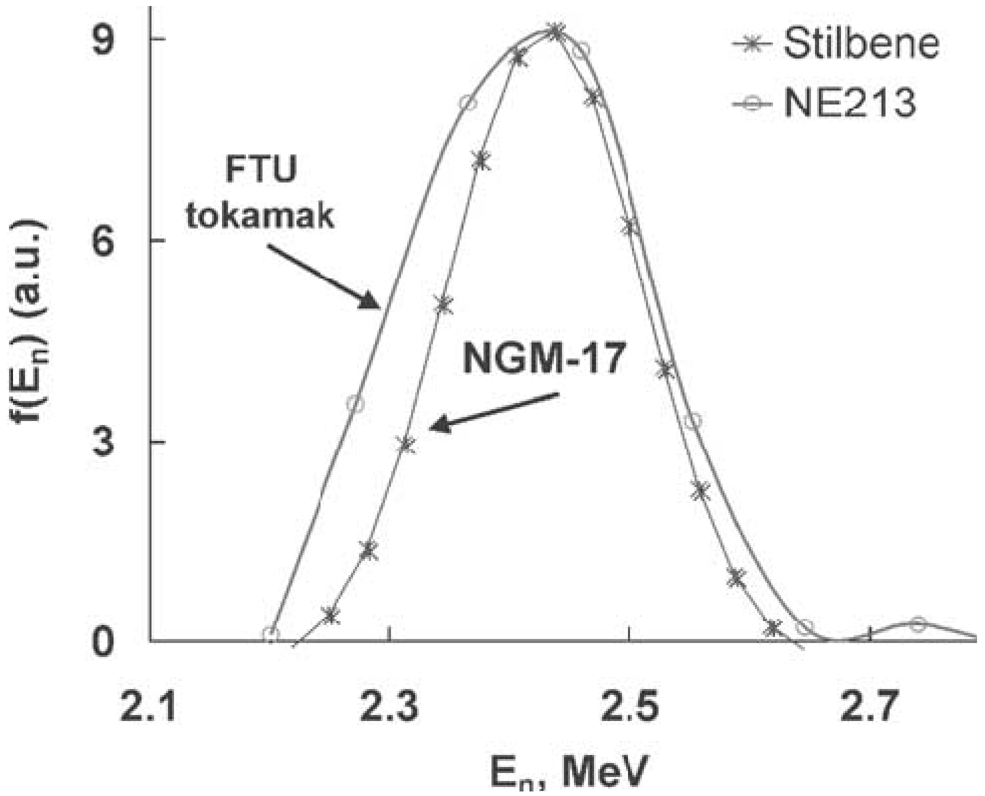

Fig. 32: D-D neutron spectrum of the FTU tokamak measured with NE213 and neutron spectrum of a D-D neutron generator (NGM-17) measured with a stilbene detector

Since 15 years radiation protection studies supporting the design of European and international thermonuclear fusion devices have been performed by the Radiation Protection Institute at ENEA Frascati. These studies aimed at assessing individual and collective doses and also at designing the radiation monitoring and control systems. In the near future the monitoring systems developed with the support of ENEA will be implemented at ITER and at some side projects like NBTF (Neutral Beam Test Facility) in Padua, Italy. The components and the architecture of these systems are similar to that developed for the accelerator facilities and used at the Frascati fusion experiments supporting devices described above.

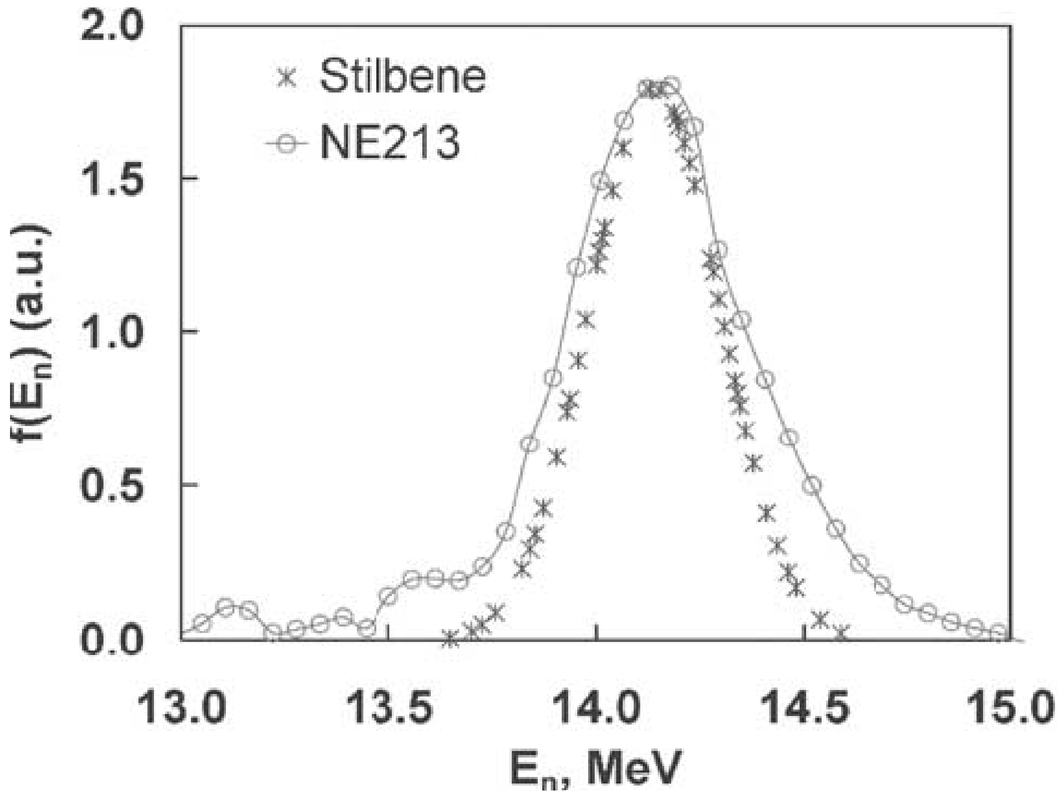

Fig. 33: Neutron spectrum of the D-T neutron generator FNG measured with NE213 and neutron spectrum of another D-T neutron generator (VNIIFTRI) measured with a stilbene detector

4.2.1 Radiation monitoring at the Frascati nuclear fusion facilities

The radiation protection program for FTU and FNG is based on two independent monitoring systems: an active monitor network and passive dosimetry stations. Mixed, pulsed and triggered radiation fields are measured with these systems.

At the FTU experimental nuclear fusion device eight active monitoring stations are installed, each composed of a BF_3 rem counter and a proportional gamma counter or an ionization chamber. The monitoring stations are located at the three levels of the main FTU building. Four are located in the main hall in which the facility is hosted. In this area four plastic (tissue equivalent) ionization chambers are used to prevent neutron activation of their walls. Due to the short plasma burning period of FTU (about 1 s) almost all the monitors are triggered to record the measured dose during burning time only. Only the four plastic ionization chambers inside the main hall that are used to measure the residual radioactivity from neutron activation are not triggered. They provide continuous measurement of the dose rate and their response is included in the security chain of the access system to prevent undue radiation exposure of the workers.

The FNG facility is provided with three active monitoring stations, each composed of a BF_3 rem counter and a proportional gamma counter. The facility is located inside a single level building, in a shielded room 10 m × 10 m large and 10 m high. Two monitoring stations are located inside the building but outside the shielded room, in the access area and in the control room. The third station is located outdoor near the outer wall of the shielded room.

At both FTU and FNG passive TLD and CR39 dosimeters for environmental control are used. A total of 15 and 4 passive measurement points are located at the FTU and at the FNG buildings, respectively. In order to have a more reliable passive network, moderated TLD devices for fast neutron dosimetry have been designed and tested at the ENEA Frascati Research Centre and are used for environmental measurements in mixed gamma and neutron radiation fields around the FNG and

FTU fusion facilities. The dosimetric device is composed of four LiF:Mg,Cu,P pellets, two enriched with ^{7}Li and two enriched with ^{6}Li, enclosed in a polyethylene cylinder that acts as moderator. A Monte Carlo simulation using the MCNP-4C code was used in the design phase to analyse the detector response to neutrons produced by D-D and D-T reactions. In the experimental phase the device was irradiated with neutrons produced at FNG in order to determine the relevant calibration parameters.

4.3 ITER (International Thermonuclear Experimental Reactor)

ITER will be the first experimental reactor to demonstrate the extended burn of deuterium-tritium plasmas at a few hundred MW of fusion power and with the key technologies recognised as essential to a power reactor. The revised performance specifications adopted by the ITER Council and published in the 2001 Final Design Report (FDR) require ITER:

– to achieve extended burn in inductively-driven deuterium-tritium plasma operation with $Q \geq 10$ (Q is the ratio of fusion power to auxiliary power injected into the plasma), not precluding ignition, with an inductive burn duration between 300 and 500 s,

– to aim at demonstrating steady state operation using non-inductive current drive with $Q \geq 5$.

In terms of engineering performance and testing, the design should:

– demonstrate availability and integration of essential fusion technologies,

– test components for a future reactor,

– test tritium breeding module concepts, with a 14 MeV-neutron power load on the first wall ≥ 0.5 MW/m^2 and fluence ≥ 0.3 MWa/m^2.

In addition, the device should:

– use as far as possible technical solutions and concepts developed and qualified during the previous period of the engineering design activity,

– cost about 50% of the direct capital cost of the 1998 ITER Design.

One of the foremost goals of ITER is to demonstrate the safety and the environmental potential of fusion power. Extensive design and assessment activities are undertaken to ensure the safety and environmental acceptability of ITER and to ensure that ITER can be sited in the territory of any of the Parties with only minor changes to accommodate or take advantage of site-specific features.

4.3.1 ITER project for the Radiological Monitoring System

The fact that the total neutron yield at ITER is expected to be about three orders of magnitude larger than that of the JET facility presents a severe challenge for radiation protection dosimetry at workplaces. The primary function performed by the ITER radiological monitoring and protection system (RM&PS) is to provide protection of personnel from penetrating ionizing radiation. The function is accomplished by a combination of fixed and movable radiation/contamination monitors working in conjunction with a dosimetry and bioassay system. The function is implemented on a local and plant-wide basis by providing active monitoring with readout and alarms for local personnel response.

The RM&PS first assesses the radiation and ventilation zones for each building that contains or may contain radioactive material and direct radiation. From this assessment a general monitoring plan is developed by the Health Physics staff for each location in the building. The general plan is reviewed by the building and equipment task officers and if acceptable, a monitor layout and coverage diagram is developed. Data from the monitoring system may be useful for protecting machine components and equipment, but this is not an explicit requirement for the system. The system responsibility is limited to protection of workers and controlling and monitoring effluent releases. Tritium inventory control (accountability) is also outside the scope of this system.

Contamination control is supported by information obtained from airborne tritium (constant air volume) monitors, particulate-in-air sampling and analysis, and surface monitoring by manual sampling with sample counters. Direct gamma ray monitors are used where levels above background are expected. These fixed monitors will be supplemented by portable monitors. All fixed monitors of all types are networked to central monitoring locations in the personnel building and in the control building.

Apart from the radioactive waste storage building, the main source for gamma radiation for most of the buildings is the tokamak and the hot cell where tokamak parts will be processed and stored. The most intense radiation will arise during plasma burns, particularly D-T plasmas, but radiation from activated components between shots and during shutdowns will be significant. Hence gamma radiation monitors should be located in positions that take into account the direction of the source.

The indicators for siting gamma monitors are:

- in any room, on a wall closest to the tokamak,
- close to any penetrations that leads in the direction of the tokamak,
- close to path which in vessel components will take,
- close to areas where activated components will accumulate, such as in the hot cell.

These indicators are not comprehensive and other factors may determine the final location of a monitor in any area. Such measures have a good probability of indicating the highest gamma levels in any particular area. The radioactive waste building and the hot cell, in addition, will have monitors located close to areas where radioactive materials will accumulate. All rooms should be equipped with a facility where the gamma levels can be estimated before entry using survey instruments, such as a thinned-down section of a door or wall normally covered by a plug.

Many siting principles for neutron monitors follow closely those of gamma monitors as the prime source is the tokamak. It should be noted that neutrons are produced only in the tokamak plasma, in the NB injectors, and possibly in the cooling water (^{17}N). Because of scattering they can penetrate more easily than photons labyrinths and ducts traversing biological shields.

5 Development and research work in instrumentation and dosimetry

There is quite a lot of research and development work going on in the field of radiation protection dosimetry and instrumentation. Without the presumption of being complete, this section illustrates the major developments taking place in the field at several institutes and international organizations throughout Europe.

5.1 Institut de Radioprotection et de Sûreté Nucléaire (IRSN)

The Laboratory of Ionizing Radiation Dosimetry (LDRI) of the External Dosimetry Department at IRSN owns different devices to perform expertise measurement campaigns in most radiation fields. Recently, for applications in the medical domain, the laboratory used a TEPC (Tissue Equivalent Proportional Counter) initially developed for dosimetry of cosmic rays onboard airplanes. This device measures different types of particles, neutrons, photons, protons, ions and muons. Calibration of TEPC was performed with an Am-Be reference source at IRSN (Cadarache, France) and with ^{60}Co and ^{137}Cs sources at IRSN (Fontenay, France). The characterization of the response to neutrons over a wide energy range (0.5–100 MeV) of this counter was done with monoenergetic fields at standard laboratories: PTB (Germany), UCL (Belgium) and iThemba-lab (South Africa) (see Section 6.3.1). Some measurements in broad energy neutron fields were performed at the CERF facility at CERN (see Section 6.4.1), and at the SILENE reactor at CEA. The LET range of this device extends from 0.3 to 1020 keV/µm, but a significant underestimation is observed for neutrons below 500 keV. Some future work concerns mainly the determination of a correction factor for pulsed radiation fields and the characterization in ion beams and high-energy photon fields at PTB.

The TEPC is used for measurement of the secondary radiation field in proton therapy (mainly high-energy neutrons), as well as secondary neutrons produced in high-energy photon therapy facilities. Dosimetric measurements of radiation field around experimental reactors and measurements of cosmic radiation on board aircrafts are also foreseen [86].

For reference dosimetry in high dose-rate mixed radiation fields (neutrons and photons) and in high-energy proton beams, the LDRI developed the application of passive dosimeters based on electron spin resonance (such as alanine and sucrose). This technique can be used for various particles, neutrons, photons, protons, ions, muons, etc. These dosimeters present tissue equivalence over a large energy range for photons and neutrons. Until now the application in mixed radiation fields needed an additional TLD. The characterization and the calibration of these passive dosimeters were performed at ICPO (Orsay, France) for high-energy protons, at the experimental reactor SILENE at CEA-Valduc for fissions neutrons and at the neutron therapy facility in Orléans (France) for 20 MeV neutrons.

Future work concerns the characterization for thermal and high-energy neutrons as well as for ion beams. Some improvements in the response is expected by adding doping material (such as ^{6}Li and boron), and some work related to the improvement of the signal processing is in progress in order to determine the photon and neutron components in a mixed radiation field from the sole ESR measurement of alanine.

The laboratory for neutron metrology and neutron dosimetry owns and maintains several neutron users' facilities available for calibration of radiation protection devices. Various spectrometers are used to characterize those neutron fields and, on request, fields encountered at workplaces. To fulfil the need of neutron spectrometry measurements around medical electron linacs, the laboratory is developing a passive neutron Bonner Sphere Spectrometer. This device consists of activation foils as thermal detectors, placed in polyethylene moderating spheres, and allows neutron measurements in the energy range from thermal to 20 MeV. The Monte Carlo calculated fluence response functions will be experimentally verified with IRSN mono-energetic neutron beams and in broad energy neutron fields (radioactive sources and workplace fields) at CANEL and AMANDE (see Sections 6.4.2 and 6.3.4.2).

The development of an extended active Bonner Sphere Spectrometer for high-energy neutrons is also under study, for applications related to the medical domain, in particular proton therapy with high-energy (up to 200 MeV) proton beams. High-energy standard neutron beams will be needed for validating the calculated response functions.

5.2 Grup de Física de les Radiacions, Universitat Autónoma de Barcelona

The Grup de Física de les Radiacions (GFR) Universitat Autónoma de Barcelona has been developing since year 2000 a new activity concerning neutron spectrometry and dosimetry in nuclear power plants and medical accelerators. For the spectrometry in nuclear power plants the GFR, in collaboration with the French Institute for Radiological Protection and Nuclear Safety (IRSN), has developed an active neutron Bonner Sphere Spectrometer (BSS). This device consists of a new ^{3}He proportional counter (model 0,5NH1/1K1 developed by Eurisys Mesures, France) as thermal neutron detector, placed in the centre of polyethylene moderating spheres which allows neutron measurements in the energy range from thermal to 20 MeV. The fluence response functions were calculated with the MCNPX Monte Carlo code and the system characterized with monoenergetic neutron beams and ISO sources at PTB and IRSN. Upon request from the Spanish National Nuclear Safety Council, the GFR was in charge of characterizing the neutron fields at several measurement points (a total of 17) inside the containment building of Vandellos II, Asco I, Asco II and Cofrentes, using this active BSS and the home made MITOM unfolding code.

In the case of medical accelerators, due to high frequency electromagnetic fields and to the presence of abundant leakage and scattered photons, measurements of the corresponding neutron fields by active dosimeters are extremely difficult. For this purpose the GFR, again in collaboration with IRSN, has developed a Bonner sphere set employing gold foils as thermal neutron sensor for application in pulsed neutron fields or in mixed fields with high photon intensities, where active devices suffer from saturation and dead-time effects. The system was simulated with MCNPX to determine the fluence response functions of each sphere to neutrons of different energies. The BSS was characterized with monoenergetic neutron fields and with a ^{252}Cf ISO source at the IRSN facilities.

The development of an extended-range, active Bonner Sphere Spectrometer for high-energy neutrons is also being studied, for applications in the medical domain, in particular proton therapy with high-energy proton beams. Facilities with high-energy reference beams will be needed for validation of the simulated fluence response functions

5.3 Radiation monitoring for the LHC at CERN (RAMSES project)

CERN has designed a new radiation monitoring system for the LHC, which represents an evolution of the present system (the ArCon discussed in Section 3.1.1.1). The RAdiation Monitoring System for the Environment and Safety (RAMSES) (87, 88) consists of about 350 monitors, which will measure ambient dose equivalent rates in the LHC underground areas as well as on the surface inside and outside the CERN perimeter. In addition, the system will monitor air and water released from the LHC installations. The RAMSES architecture is illustrated in Fig. 34. The system will have to cope with two principal monitoring conditions related to the LHC beam status: BEAM-ON and BEAM-OFF. During BEAM-ON, RAMSES will monitor stray radiation (neutrons, relativistic charged particles, photons and muons) in areas accessible during beam operation. During BEAM-OFF, it will monitor dose rates caused by radioactivity induced in accelerator components and their surroundings and by X-rays generated by RF cavity operation during shutdown periods.

RAMSES will also provide the proper means to assess the effective dose to the population by measuring and logging stray radiation in the LHC surface areas (photons, muons and neutrons), radioactive emissions (ventilation) and effluents (water), meteorological data and by collecting aerosol samples from the environment. The system will also calculate the released activities of very short-lived radionuclides monitored on-line, such as ^{11}C, ^{13}N, ^{14}O, ^{15}O and ^{41}Ar in the ventilation, or ^{24}Na in liquid effluents.

The monitors employed by RAMSES are an advanced version of those presently in use at CERN. Once RAMSES will be operational at the LHC, it will eventually be extended to replace the present ArCon system in use around the existing CERN accelerators.

A major challenge for RAMSES was the development of new electronics hardware in order to measure low radiation at background levels as well as high radiation levels up to several tenths of µGy per pulse, both under pulsed radiation conditions. A specially developed electronics, designed to measure the charge issued from ionization chambers is able to measure reliably over 9 decades without changing the measuring range. The last point was a crucial one since commercially available electronics usually make use of dynamic range switching. This fact made it impossible to use such electronics in a pulsed radiation environment. The new electronics makes use of an adaptive charge digitizer, an advanced version of the formerly used digitizer technique.

RAMSES also integrates other radiation measuring equipments like hand-foot-monitors and tools and material controllers. The typical distances between CERN sites and the size of CERN installations required all equipment being designed and integrated into RAMSES in order to maintain and configure the system remotely.

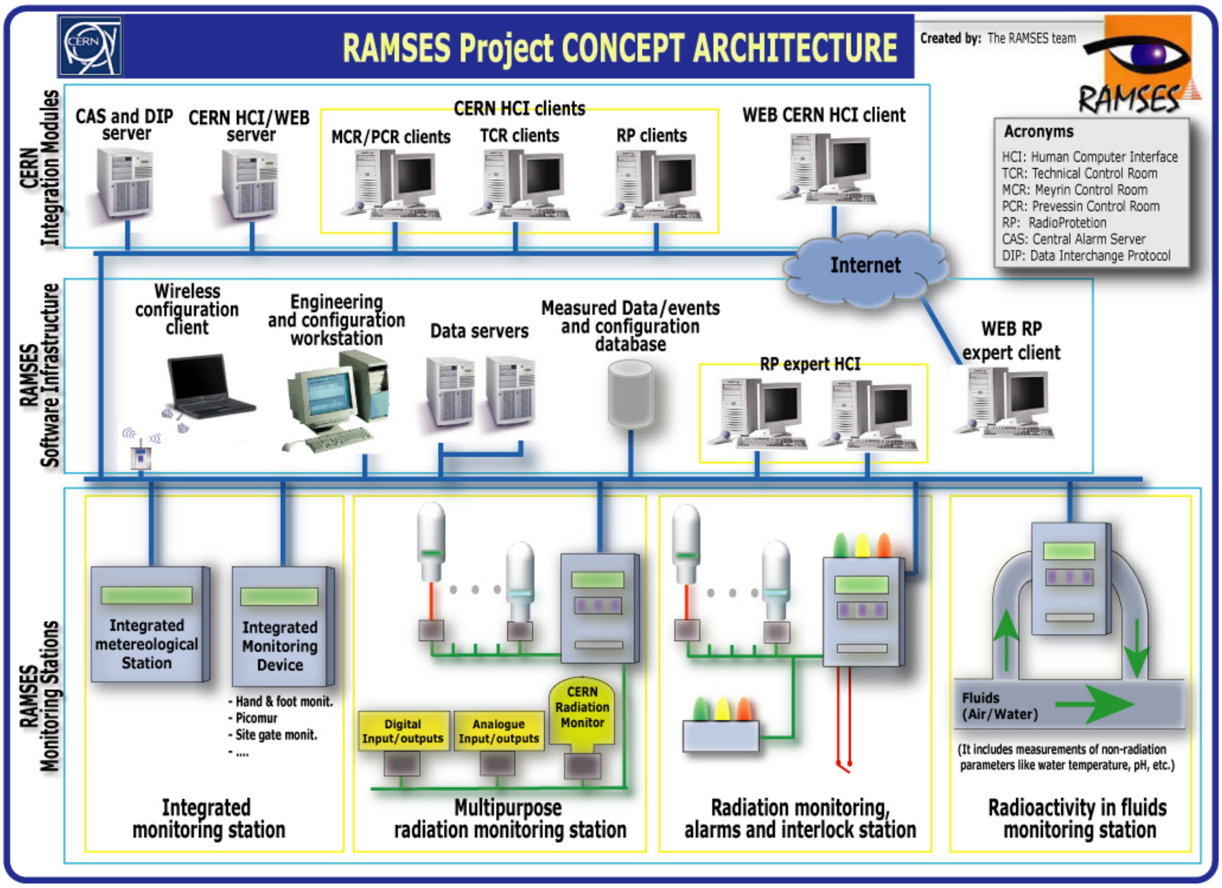

Fig. 34: The RAMSES architecture

5.4 Institute of Atomic Energy, Swierk, Poland

Research and development in dosimetry of complex radiation fields started at the Institute of Atomic Energy (IAE) Swierk in Poland in the early 1960s, based on the idea of using the initial recombination of ions in pressurized gases to determine the relative biological effectiveness (RBE). Since that time the Laboratory of Mixed Radiation Dosimetry at the IAE formed a research group strongly specialized in the development of recombination methods and in the design of recombination chambers optimized for different irradiation conditions. There are few tens of different models of recombination chambers developed up to now for radiation protection and beam dosimetry.

Recombination methods [67, 89] make use of the fact that the initial recombination of ions in the gas cavity of the ionization chamber depends on local ionization density. The latter can be related to the linear energy transfer (LET) and provides information on the radiation quality of the radiation field. Another key feature of the initial recombination is that it does not depend on dose rate.

Conditions of initial recombination can be achieved in specially designed high pressure tissue-equivalent ionization chambers, called recombination chambers. They are usually parallel-plate ionization chambers filled with a tissue-equivalent gas mixture to a pressure of the order of 1 MPa. The spacing between electrodes is of the order of millimetres. At larger spacing, the volume recombination limits the maximum dose rate at which the chamber can be properly operated. Sets of electrodes connected in parallel are used to increase the chamber sensitivity.

The chambers can be used for the determination of dose equivalents of any external radiation, also in complex radiation fields [89] of poorly known composition and energy spectrum, including pulsed radiation fields [90]. Tissue-equivalent chambers can be also used for the determination of the photon and neutron components of the absorbed dose in mixed neutron-gamma fields and for the estimation of the dose distribution versus LET.

The output of the chamber is the ionization current (or collected charge) as a function of collecting voltage. Most of the recombination methods require the measurement of the ionization current (or charge) at least at two values of the collecting voltage applied to the chamber. The highest voltage should provide the conditions close to saturation (but below discharge or multiplication). The ionization current measured at the maximum applied voltage is proportional to the absorbed dose *D*. Measurements at other voltages are needed for the determination of the radiation quality.

The total dose equivalent in a mixed radiation field is given by the product $H = D{\cdot}Q$ of the absorbed dose *D* and radiation quality factor *Q*, both determined by the recombination chamber.

Two different methods were proposed for the determination of the radiation quality factor, both based on the fact that the dependence of initial recombination on LET is different for different collecting voltages applied to the chamber. The first, simpler approach involves measurements of the ionization current at two properly chosen collecting voltages [91, 92]. A certain combination of these two currents may serve as a measurable quantity which depends on LET in a similar way as the quality factor defined in ICRP Publication 60 [93] in different mixed radiation fields including neutrons of energies from thermal to few hundreds MeV [89, 94].

The second method [95] involves measuring the ionization current of the recombination chamber at several collecting voltages and determining the dose distribution *D(L)* versus LET. The *D(L)* distribution is then used for determination of the low-and high-LET dose fractions and for calculation of the radiation quality factor.

The main goal of radiation protection dosimetry at workplaces is the determination of the ambient dose equivalent, $H^*(10)$. At present, the best recombination chamber investigated for this purpose is the REM-2 chamber [96] designed at IAE and manufactured by POLON Bydgoszcz (Poland). The energy dependence of the REM-2 chamber response to $H^*(10)$ was investigated in monoenergetic neutron beams with energy ranging from 75 keV to 19 MeV [93] and in radiation fields of isotopic neutron sources [97]. The results obtained with high-energy neutrons (CERF calibration fields [98, 99] and therapeutic neutron beam with mean energy of 350 MeV in JINR Dubna [100]) showed an agreement of better than 10% compared to the reference methods. The $H^*(10)$ response of the REM-2 chamber to photons is about 15% lower then the response to ^{241}Am-Be neutrons.

The main advantages of the REM-2 chamber are: response close to $H^*(10)$ for all types of penetrating radiation, high reliability during many years [89, 93, 100] and easy handling with no need of service. With such features the chamber can be especially suitable for continuous monitoring of complex mixed radiation fields.

The chamber was initially designed for measurements in mixed radiation fields near nuclear facilities, high-energy accelerators and with isotopic neutron sources. Therefore, the parameters of the chamber were adjusted to optimize the measurements at dose rates above 1 μGy h^{-1}. This limit can be extended to lower values using a specially modified chamber and special mode for powering the chamber and reading the signal. Such modified chamber can be used for measurements of low dose equivalent rates, e.g. in cosmic radiation fields [101].

Current research projects at the IEA include:

- comparison of different recombination methods in high-energy mixed radiation fields,
- development of a measuring system for dosimetry of neutrons generated at medical accelerators. The system consists of an in-phantom tissue-equivalent recombination chamber and associated electronics for automated control and data acquisition,
- development of recombination chambers containing boron,
- development of recombination detectors for boron neutron capture therapy,
- investigations of initial recombination in gamma- and X-ray radiation fields and in gas mixtures at high pressure.

5.5 INFN – LNF Radiation Protection Group (Frascati, Italy)

The Radiation Protection Group of the INFN Frascati Laboratories is operating in the field of neutron dosimetry and spectrometry, with the specific aim of developing operational techniques, instruments and software for improving the quality of the dosimetric surveillance of workers and areas around the Frascati DAΦNE 510 MeV e^+/e^- collider. The following neutron irradiation facilities are available at the LNF:

- low scattering neutron calibration room (around 15 m × 10 m × 5 m height, with aluminium roof) where a precision optical bench allows dosimeters and survey-meters to be calibrated with the shadow cones technique and the other procedures reported in ISO Standard 8529-2. An Am-Be source is used and efforts are planned to buy a Cf source,
- BTF (beam test facility). A 500 MeV to 800 MeV electron beam can be extracted from the main linac and sent to a dedicated experimental area, normally used for testing high-energy physics detectors. By using an optimized lead target, neutron beams have already been produced and preliminary neutron measurements have been made. The radiation protection group and the BTF group are planning to establish an on-target irradiation geometry and a beam monitoring system in order to use the facility for neutron dosimetry/spectrometry exercises and inter-comparisons.

As far as dosimetry and spectrometry are concerned, the Group operates the following techniques.

5.5.1 Active and passive Bonner Spheres (BSS)

5.5.1.1 Active system

A commercial Ludlum system based on a 4 mm × 4 mm ^{6}LiI(Eu) scintillator has been characterized and used to obtain the neutron field at workplaces, such as the monitoring points around DAΦNE. Six polyethylene spheres (2", 3", 5", 8", 10" and 12" in diameter) and one lead-loaded 12" sphere are used. Validation measurements have been made with radionuclide sources and monoenergetic neutrons at the ENEA Frascati Fast Neutron Generator (FNG) (2.5 MeV and 14.2 MeV). Additional validation measurements were made early in 2006 during an experimental campaign at the Geel JRC Van der Graaff (monoenergetic neutrons from hundreds of keV to 20 MeV), in the framework of the EU NUDAME program.

5.5.1.2 Passive system

The same BSS has been used with gold foils and TLD pairs to determine the neutron spectrum around medical linear accelerators. The TLD based BSS are also used for long integration time environmental measurements around the DAΦNE accelerator. The validation of the gold and TLD response functions, up to now only done with Am-Be sources and a thermal field, was completed during the Geel campaign.

5.5.2 Thermoluminescent detectors

The historical experience with the TLD pair technique, based on TLD600 and TLD700 or TLD600H and TLD700H, has been enhanced by studying the Polish ^{6}LiF(Mg,Cu,P) materials (from TLD Poland). This material is especially customized with thin sensitive layer in order to obtain very high neutron to photon discrimination capability, together with very high thermal neutron sensitivity. These TLDs, which performance in low-intensity neutron field is very promising, are used for environmental dosimetry and inside the BSS.

5.5.3 CR-39 dosimetry

A chemically etched CR-39 dosimetry system is operating for routine environmental monitoring. The dosimeters are analyzed with an automatic reader developed at the Frascati laboratory, equipped with motion and vision tools, which is able to give a rough energy indication on the examined dosimeter. Small processing time and immediate data storing and reporting procedures make the reader suitable for both routine and research.

Studies for improving the high-energy response of the dosimeter with lead filters are in progress. Irradiations have been done with radionuclide source and 2.5/14.2 MeV monoenergetic neutrons. The complete energy response curve was determined at the Geel campaign.

5.5.4 Rem counters

The Group employs rem counters with different energy response in order to assess the quality of the neutron beam during routine measurements. In particular, the LB6411 rem counter is used with and without a 1 cm lead shell for determining the high-energy neutron component of the field. Use is also made of the original LINUS rem counter.

5.6 Improvements of the CR-39 personal neutron dosimetry system at PSI

The CR-39 type PN3 neutron detector from Thermo Electron Corporation is used for individual monitoring at PSI since 1998. The badge can be equipped with different radiators, in order to cover different energy regions. Polyethylene (PE) is used to enhance the fast energy neutron response. A PE/Li (1% $LiNO_3$) radiator gives a pronounced efficiency for thermal neutrons and the use of an aluminium plate results in spectral information in the fast neutron energy region. For fast and high-energy neutron dosimetry a simplified version, using the housing material (PA6 and PA12) as converter is applied. The readout of the detector is based on a chemical etching procedure combined with a well suited optical counting system.

Further developments of the system consist of:

- studies on the reduction of artefacts in the track structure and size distribution,
- determination of the long term (up to one year) stability of the detector sensitivity and background track density (Fig. 35 and Fig. 36). Over one year the background track density increases by a factor of 2. The sensitivity of the detector decreases by a factor of 2, when irradiated after one year (aging effect) and the fading of the tracks of irradiated detectors varies between 0% and 15% over one year,
- investigation of the response to mixed and high-energy radiation fields in special experiments performed by various organizations.

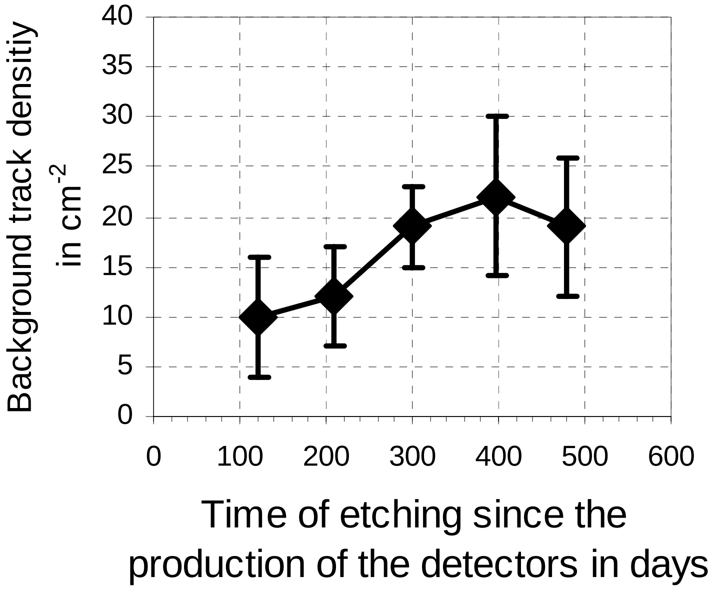

Fig. 35: Background track density, as a function of the age of the detectors

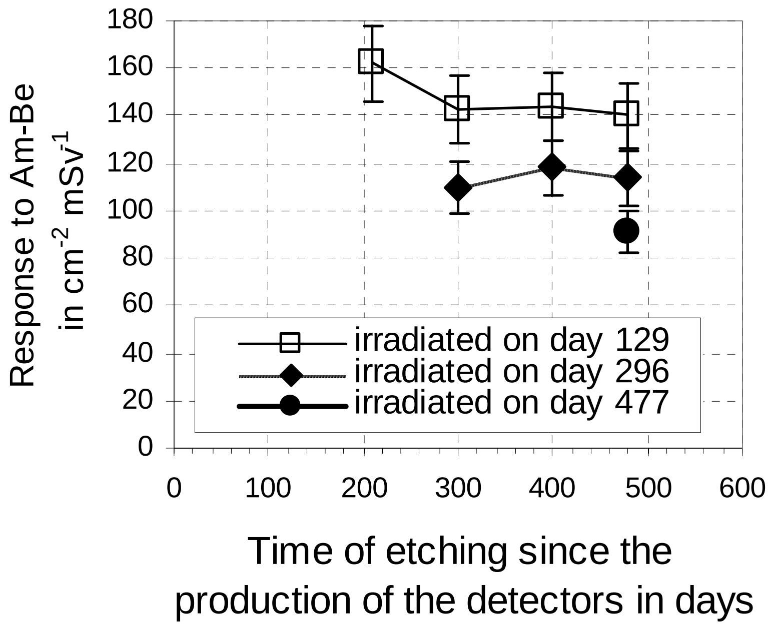

Fig. 36: $H_p(10)$ neutron response to Am-Be as a function of the age of the detectors and the time of irradiation and etching

5.7 Nuclear Physics Institute, Czech Academy of Sciences

The Nuclear Physics Institute of the Czech Academy of Sciences (NPI AS CR) started to use and develop instrumentation for dosimetry in mixed (mostly gamma-neutron) radiation fields since the 1970s. Particularly important has been the period since 1990s, when the studies already performed around the accelerators of the Joint Institute of Nuclear Research, Dubna, Russia, and those onboard spacecrafts, have been enlarged to onboard aircraft radiation fields. Several equipment and/or dosimeters have been and are used and developed. These are briefly discussed below.

5.7.1 Equipment used to characterize the non-neutron component

Three types of commercially available personal electronic dosimeters (PED) have been used, two based on a Si-detector, one on a GM-counter. All are able to measure the dose equivalent rate up to values of the order of Sv per hour; the minimum integrated dose equivalent is around 1 μSv.

High pressure argon-filled steel ionization chamber from Reuter Stokes is taken as a reference instrument for environmental external radiation measurements. The chamber can measure the exposure rate from values corresponding to a fraction of the natural background up to ambient dose equivalent rates of the order of 1 mSv per hour.

The scintillation counter for environmental radiation measurements NB 3201 [(102)] is also devoted to environmental external radiation measurements at the level of natural background. Its sensitive element is a plastic scintillator incorporating a small NaI:Tl crystal to compensate for the energy dependence.

Two thermoluminescent detectors (Al_2O_3:C and Czech Al-P glasses) were used to characterize mostly the non-neutron contribution to the total equivalent dose. They have been studied at NPI since several years, including their responses to high LET charged particles [(103)]. Their thermoluminescence yield (light conversion factor) decreases with increasing LET of the particle transferring the energy above about 10 keV/μm, more rapidly for Al_2O_3:C than for Al-P glasses.

Detectors and instruments devoted to characterize this component of onboard radiation field were primarily calibrated in a reference beam of ^{60}Co photons. The readings have been treated in terms of ambient dose equivalent $H^*(10)$. The same detectors were also tested at the CERF high-energy reference radiation facility discussed in Section 6.4.1. It was found that the response of PED based on the Si-diode are, when expressed as mentioned above, about 30% lower than for other instruments.

Obviously all these detectors have also some response to the neutron component. It was established that the relative response (in terms of tissue kerma) of TLDs to fast neutrons does not exceed 10%, whilst for high-energy neutrons it can reach more than 50% [(103, 104)]. In terms of $H^*(10)$, it would be roughly 10 times less.

5.7.2 Equipment used to characterize the neutron component

The moderator type dose equivalent meter NM2 used at NPI is based on the Andersson–Braun rem counter with a BF_3 proportional counter at the centre of a cylindrical moderator (see Section 2.1.1). The dynamic range of dose equivalent rate is between 300 nSv and 1 mSv per hour.

Bubble damage neutron detectors are discussed in detail in Section 2.1.3. NPI has used those available from BTI (BDND) types PND and BD100R with nominal sensitivity of about 1 bubble per μSv of $H^*(10)$ of AmBe neutrons. A few measurements have also been performed with the BTI bubble damage spectrometer. Superheated drop detectors (SDD) [(22)] have also been used and studied, with neutron energy thresholds of 0.1, 1.0 and 6.0 MeV.

Electrochemically etched polyallyldiglycolcarbonate (PADC) track detectors [(42)] available from Pershore Ltd., UK, have been used as neutron dosimeter. They have an energy threshold of about 100 keV. Two etching methods are used, the first one consisting of chemical pre-etching (CE) followed by high frequency electrochemical etching (ECE), the second one consisting of subsequent low and high frequency ECE. During irradiation, CR39 samples were covered by 2 mm thick polyethylene (PE).

Detectors and instruments devoted to characterize the neutron component were calibrated using a bare AmBe and/or a ^{252}Cf radionuclide neutron source. The reading was also treated in terms of ambient dose equivalent $H^*(10)$. The detectors have been regularly tested in the CERF fields discussed in Section 6.4.1. For higher neutron energies their response decreases. The responses of passive neutron detectors relative to the CERF neutron reference values are shown in Table 7. The relative response of the NM 2 rem counter was in the CERF high-energy field equal to 0.54 ± 0.04.

Table 7: Relative responses of passive neutron detectors to CERF neutrons (top concrete shield)

Neutron detector	**Relative response to CERF reference values**
BD 100R	0.72 ± 0.07
PND	0.53 ± 0.06
SDD 100	0.72 ± 0.05
PADC combined etching	1.02 ± 0.15
PADC two frequency EC etching	0.45 ± 0.07

5.7.3 Equipment used to characterize the full radiation field

At present no TEPC equipment is owned by NPI, but some experience exists with the NAUSICAA developed in France. The Mobile Dosimetry Unit (MDU) is a semiconductor spectrometer [(105, 106, 107)] that monitors the doses and numbers of energy deposition events in the detector. The amplitude of the pulses is proportional to the energy deposited in the detector. The adjustment of the energy scale is made through the 60 keV photons of ^{241}Am. The amplitudes are digitized and organized in a 256-channel spectrum. The dose D in Si [Gy] is calculated from the energy deposition spectrum as:

$$D = K \cdot \Sigma(E_i \cdot A_i)/M$$

where M is the mass of the detector, E_i is the energy loss in channel i, A_i is the number of events in it and K is a coefficient.

The response of the equipment was studied with reference ^{60}Co photons, fast neutrons and in the CERF fields. It was observed that there is a principal difference in the shape of the energy deposition spectra in Si for low- and high-LET radiation. On this basis the spectra have been divided in two parts, one mostly corresponding to the non-neutron component of a radiation field, the other to the neutron-like component. The calibration factors were deduced from the H*(10) reference values in the CERF reference fields. The results obtained are taken as “apparent” dose equivalent, H_{app}, in a high-energy radiation field. It was also observed that the energy deposition spectra observed onboard aircrafts and/or at high mountains are similar to those measured in the CERF field. The relative response of the equipment as a function of neutron energy has also been studied [(106)]. It has been found that directly measured event deposition spectra onboard aircrafts treated in this way give a reasonable estimation of the radiation exposure level onboard aircraft [(107)].

5.8 The PTB NEMUS, neutron spectrometry in high-energy neutron environments

The PTB NEMUS (NEutron MUltisphere Spectrometer) serves as a reference system for the spectrometry and dosimetry of unknown neutron fields in the energy range from thermal neutrons up to several hundreds MeV. The PTB spectrometer consists of a set of ten Bonner spheres [(16)] of polyethylene, 7.62 cm (3") to 30.48 cm (12") in diameter. In the centre of each sphere there is a spherical proportional counter filled with ^{3}He gas of type SP9, made by Centronic Ltd., UK. New research and developments in 2000 increased the sensitive neutron energy range of the spectrometer from 20 MeV to more than 400 MeV by adding four modified spheres in which lead or copper shells are embedded in the polyethylene (see Fig. 1 and Fig. 2 in Section 2.1.2) [(108)].

The determination of the neutron spectrum $\Phi(E)$ requires *deconvolution* (unfolding) of the primary measured data, i.e. the count rates N_d of each sphere d in a neutron environment, from the relation $N_d = \int R_d(E)\ \Phi(E)\ dE$, where $R_d(E)$ is the response function of sphere d.

The response functions were calculated for a long list of monoenergetic neutron beams with energies between 1 meV and 10 GeV using the MCNP and MCNPX codes. The most important step in the characterization of this spectrometer is the validation of the calculated responses in monoenergetic or quasi-monoenergetic neutron calibration fields. The determination of an appropriate calibration factor enables the use of the response functions on an absolute scale. Furthermore, this allows the measurement of absolute fluence rates and via folding with the fluence-to-dose conversion coefficients $h_{\Phi}(E)$ the measurement of absolute dose rates. The total neutron fluence can be determined by suitable deconvolution methods with uncertainties of the order of 5%. Dose equivalent quantities [e.g. the ambient dose equivalent, $H^*(10)$] can be determined from the neutron spectrum with uncertainties in the order of 15%. This implies the necessity and the requirements for well characterized calibration fields (see Section 6).

At PTB there is a long history of expertise in the field of neutron spectrometry, including the development of numerous deconvolution methods and programs (109, 110). NEMUS has been used in a variety of settings, including measurements at workplaces in nuclear industry and aircraft as well the investigation of the neutron component of cosmic radiation on the ground where neutron energies of up to 1 GeV have to be considered. The latest measuring campaign was assigned to measure the neutron spectrum outside a massive concrete shielding at the high-energy particle accelerator of the GSI in Darmstadt, Germany. First results can be found in ref. (111).

5.9 The extended range BSS developed by CERN and the University of Milan

The Bonner Sphere Spectrometer developed in collaboration between the University of Milan and CERN (112, 113, 114) uses the spherical Centronics SP9 ^{3}He proportional counter coupled with a set of five polyethylene spheres (diameter 81 mm, 108 mm, 133 mm, 178 mm and 233 mm) plus two newly designed for the evaluation of the neutron component above 15 MeV. The sphere with diameter 81 mm is also used with a cadmium cover. Of the two new high-energy spheres, the first has a diameter of 255 mm and consists of moderator shells of (from the central ^{3}He proportional counter outwards) 3 cm polyethylene, 1 mm cadmium, 1 cm lead and 7 cm polyethylene thickness. This configuration suppresses the response to incident neutrons with energies lower than 100 keV and increases it for energies above 10 MeV and up to 1 GeV, as compared to the 233 mm sphere of the conventional BSS. However the response function still shows the peak at about 10 MeV which is typical for all large detectors of a BSS. The second detector, with a diameter of 118.5 mm, consists of moderator shells of 2 cm polyethylene, 1 mm cadmium and 2 cm lead thickness. Its response function does not show the peak at 10 MeV, so that it is a useful complement to the other detectors. At low energies it behaves like a small Bonner sphere, but at high energies the response is increased compared to the 233 mm sphere. The response functions of the various detectors are shown in Fig. 37.

Recent measurements have provided evidence that under certain circumstances, the use of lead-enriched moderators may present a problem: these detectors were found to have a significant response to the charged hadron component which sometime accompanies the neutrons field (e.g., when measuring neutrons from an unshielded target). Conventional polyethylene moderators show a similar problem although of lesser importance. These secondary hadrons interact with the moderator and generate neutrons, which are in turn detected by the counter. To discriminate between the fractions of count-rate due to neutrons and to the charged hadron component, the response matrix of the BSS to the latter must be known (115). The response functions to charged hadrons were calculated with the FLUKA Monte Carlo code for the complete BSS, for monoenergetic broad parallel beams of protons, positive and negative pions with energy in the range 50 MeV – 150 GeV. As an example, the response functions for protons are shown in Fig. 38. For the various detectors, the response functions to protons and positive pions is quite similar, with a rapid increase up to about 100 MeV followed by a flatter trend which is due to the fact that the inelastic cross sections tend to the geometrical value. As expected, the lead-loaded spheres have a much higher response with respect to the polyethylene spheres. Negative pions show for most spheres an increased response below about 100 MeV. This is due to the fact that some negative pions can be slowed down to rest inside the sphere, are captured and produce spallation reactions. The addition of a 1 mm cadmium shell to the 81 mm sphere increases its response to charged hadrons by a factor of 5 to 10.

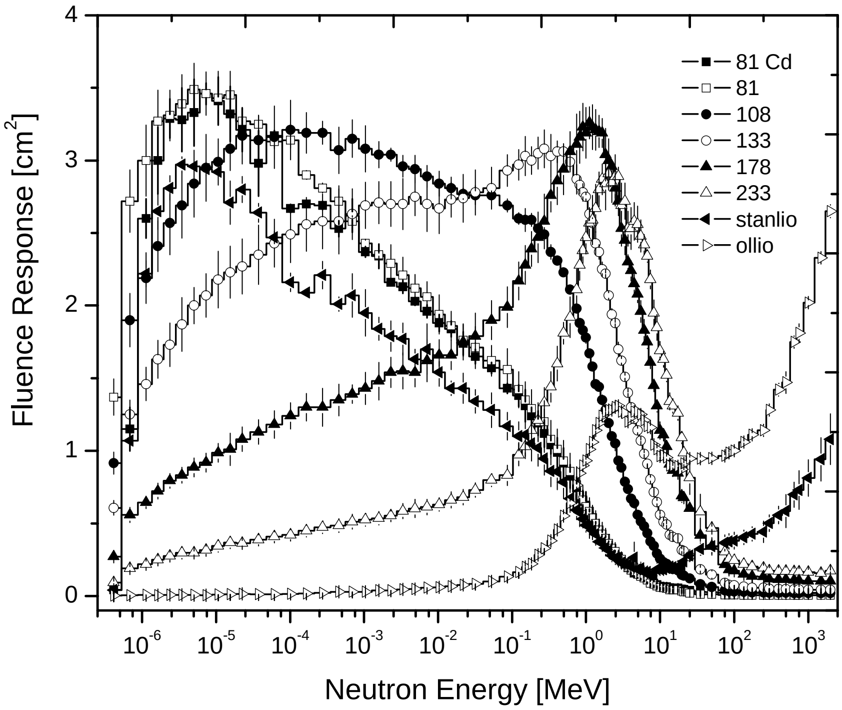

Fig. 37: Absolute neutron fluence response functions of the CERN BSS

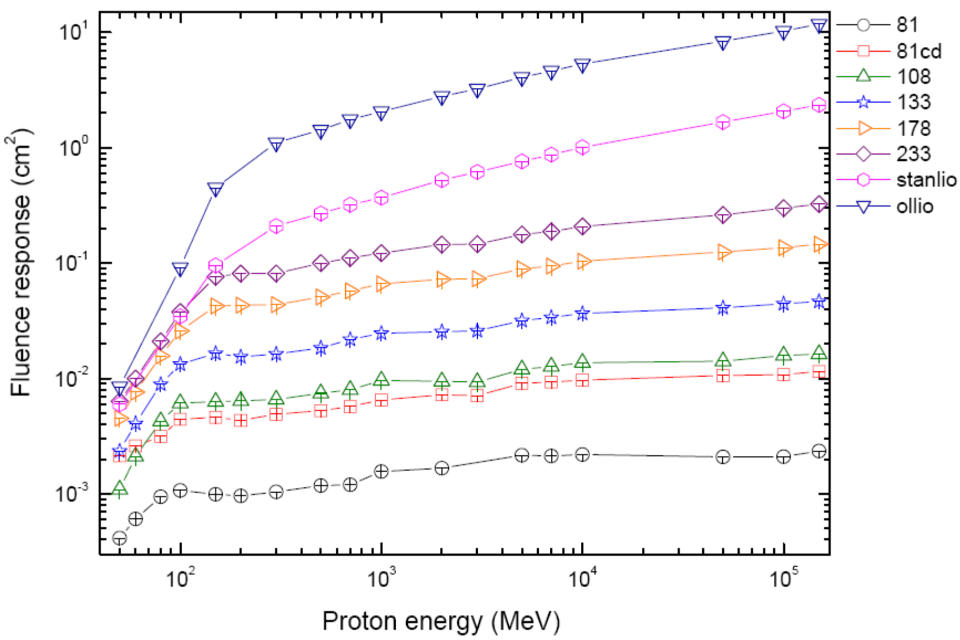

Fig. 38: Fluence response of the eight detectors of the CERN BSS to protons

6 Calibration

Calibration is the process in which the calibration factor (quotient of the conventional true value by the value indicated) of a measuring device is determined in a reference radiation field of well-known ambient dose equivalent under well specified calibration conditions (3). Radioactive sources are frequently used, e. g. ^{60}Co or ^{137}Cs sources for photon dosimeters and ^{252}Cf or ^{241}Am(Be) sources for neutron dosimeters, since they can provide stable and reproducible calibration conditions. National standard laboratories, for example, provide such reference fields. Then, if used under conditions identical with the calibration conditions, a calibrated instrument will measure $H^*(10)$ correctly. However, under different irradiation conditions, for example in fields of other particle compositions or with other particle energy distributions, deviations will occur since dosimeters used in radiation protection practice usually do not have ideal response characteristics (e. g. the same energy dependence as the fluence-to-dose equivalent conversion function). In practical applications, these deviations are either small enough for the desired degree of accuracy, or the user must apply field-specific correction factors to take the differences between calibration conditions and the conditions actually prevailing into account.

Since the radiation fields at workplaces around high-energy accelerators (but similar considerations apply for the cosmic radiation field in aircrafts responsible for aircrew exposure) differ strongly from those applied in standard calibration, the correction factors required can be large. In addition, since the field characteristics and the response of the instrument to all particles in the field are usually not well known, correction factors cannot be calculated with the desired precision. The reliability and accuracy in personnel exposure monitoring can therefore be improved by performing the calibration in the field of interest itself or in a calibration field which has similar characteristics. The direct *field calibration* of instruments in a given workplace requires a reference instrument which should be able to measure the (true value of) ambient dose equivalent (nearly) correctly for all radiation components and energies. The use of *reference fields* ('simulated workplace fields') produced under laboratory conditions requires particle compositions and spectral fluences similar to those in the workplace of interest. Those fields offer a good opportunity of investigating the dosimeter characteristics and of intercomparing different dosimeters under identical and reproducible conditions.

Photon dosimeters are conventionally calibrated with ^{137}Cs radionuclide sources emitting monoenergetic photon radiation with energy of 0.661 MeV. The reference quantity for the calibration is primarily the air kerma, K_a, which can be converted to $H^*(10)$ applying appropriate conversion coefficients. Photon dosimetry is mostly understood for pure photon fields, as discussed in Section 2.2, as well as low-energy photon spectrometry (in mixed fields the situation is more complex, as is often not easy to take into account the response of a photon spectrometer or dosimeter to neutrons). On the other hand, photon spectrometry in the high-energy region still needs a lot of development work, which is outside the scope of this report.

Reference neutron fields can be produced by radionuclide sources, by nuclear reactors and by nuclear reactions with charged particles from accelerators. A recent review of the subject can be found in ref. (116). Recommendation for producing reference neutron radiation fields are given by the International Organization for Standardization (ISO) (117, 118, 119). The calibration of neutron instrumentation is discussed in more detail in Section 6.1.

6.1 Neutron calibration fields

The calibration of instruments used for routine neutron monitoring, e.g. rem counters or personal dosimeters, is carried out using reference neutron fields with broad spectral distributions like those produced by radionuclide sources. The spectra encountered at workplaces, however, are usually significantly different from those used for the calibration. Hence the fluence response $R_\Phi(E)$ of the instrument has to be determined as a function of the neutron energy E to enable the calculation of so-called "field correction factors" which account for the dependence of the response on the neutron spectrum. The experimental determination of the response is carried out using reference fields in which the neutron fluence is concentrated at a single energy (monenergetic fields) or, at least, the majority of the fluence is at a single energy with only a smaller contribution at other energies (quasi-monoenergetic fields). The basic quantity for the specification of reference fields is the spectral neutron fluence Φ_E. The neutron ambient dose equivalent $H^*(10)$ is obtained from Φ_E by folding the spectral distribution with recommended energy dependent fluence-to-dose-equivalent conversion coefficients $h_\Phi(E)$.

Monoenergetic or quasi-monoenergetic reference fields are produced by bombarding low-Z targets (D, T, ^{7}Li) with light ions (protons or deuterons) accelerated with Van-de-Graaff accelerators or cyclotrons. In most cases monoenergetic neutrons can be obtained only under ideal conditions. In reality, however, the effects of finite target thickness, neutron scattering in the target surroundings and the finite detector size as well as break-up reactions at higher projectile energies cause deviations from the ideal situation, i.e. the fields are only quasi-monoenergetic with a high-energy peak of finite width and a low-energy continuum.

The response of a detector to high-energy neutrons (E_n > 20 MeV) is quite difficult to determine experimentally because of the low-energy tail in the spectrum provided by the available quasi-monoenergetic neutron facilities. Moreover, when measuring in unshielded radiation fields the contribution of high-energy hadrons also has to be taken into account.

If both the energy and angular response characteristics of an instrument and the energy and direction distribution of the radiation field to be determined are well known — either experimentally or theoretically — the response data can be folded with the field data to obtain a field correction factor. An alternative approach is to determine the response of the device either in the radiation field of interest (a ‘field calibration’) or in an experimental radiation field of sufficiently similar characteristics (a ‘simulated workplace field’). The availability of reference radiation facilities like CERF at CERN discussed in Section 6.4.1 or CANEL at Cadarache described in Section 6.4.2, providing particle composition and spectral fluence similar to those in workplace fields, is in this respect of obvious interest.

Modern Monte Carlo codes can help a lot in designing instrumentation and in understanding their performances and their response functions to various types of radiation. It is nonetheless important that the simulations are validated with calibration measurements in reference fields.

6.2 Thermal neutron fields

Reference radiation fields with thermal neutrons can be produced using reactors, accelerators, or radionuclide sources. Facilities of the first two types available in Europe are discussed below.

6.2.1 PTB (Physikalisch-Technischen Bundesanstalt)

The thermal reference beam (120) is installed at the research reactor FRG-1 of the GKSS research centre at Geesthacht, Germany. A bent neutron guide is used to transport thermal neutrons from the reactor to the experimental station. The basic quantity measured in this beam is the number of neutrons N integrated over the beam cross section. The spectral distribution at the irradiation position was measured using TOF spectrometry. The size of the beam spot at the irradiation position is 3 cm × 3 cm. The instruments under test are scanned through the neutron beam using a pseudo-Lissajous scanning procedure. In this way a spatially homogeneous irradiation is simulated. The scanning areas range from 5 cm × 5 cm to 60 cm × 60 cm. The average ambient dose equivalent rate d$H^*(10)$/dt at nominal reactor power is about 45 µSv/h for a scanning field of 30 cm × 30 cm. It can be further reduced without affecting the spectral distribution. Due to the bent neutron guide, the beam is virtually free of photons and epithermal neutrons.

6.2.2 NPL (National Physical Laboratory)

Thermal neutron fluence standards at NPL (National Physical Laboratory, UK) are based on a facility, commonly known as the thermal pile, which was set up in the late 1960s by Ryves and Paul [121]. The fluences of thermal neutrons are produced by moderating fast neutrons, produced by bombarding beryllium targets with beams of deuterons from a 3.5 MV Van de Graaff accelerator. The targets are located in a large graphite moderating block. Fluences are measured using the activation of thin gold foils (bare and under cadmium), and are monitored by ion chambers and fission chambers within the graphite pile.

Two locations are available for performing irradiations. One is at the bottom of a vertical, 9 cm diameter, hole giving access to a small area near the centre of the pile. At this location the fluence has a uniform spatial distribution, and fluence rates in the range from about 10^4 to 3×10^7 cm^{-2} s^{-1} are achievable. The hole diameter is, however, small and most objects, with the important exception of activation foils, have to be irradiated in the field of the “thermal column”. This is a larger diameter hole, also in the top of the pile, but in this case situated so that it is almost over one of the beryllium targets. A stainless steel tube, cadmium-lined on its curved inner surface, but not on its base, is placed in the hole. The neutron beam emerging from this tube is reasonably uniform over a circular horizontal area of about 30 cm diameter. The intensity falls off as the height increases. The maximum fluence rate achievable is only about 4×10^4 cm^{-2} s^{-1}, however, this is quite adequate for calibrating survey instruments. Personal dosimeters with reasonable thermal responses can also be calibrated although the irradiations may take a couple of hours or more. In addition to thermal neutrons the column fluence contains a component of higher energy neutrons. The spectrum of the higher energy neutrons has been measured [122], and the fast fluence has been determined relative to the thermal component. Although the higher energy fluence is only about 24% of the thermal fluence, the dose equivalent due to the fast component is more than a factor of two greater than that due to the thermal neutrons. For this reason all calibrations have to be performed with devices irradiated both bare and under a cadmium cover. There is also a photon dose equivalent rate in the beam although its value is known reasonably well.

6.3 Monoenergetic and quasi-monoenergetic fields

6.3.1 PTB, UCL and iTL

The PTB neutron metrology group makes available quasi-mononenergetic reference fields from thermal neutrons (see Section 6.2.1) to energies of 200 MeV for calibration purposes, partly in collaboration with partners from other institutions.

The monoenergetic reference fields with peak energies between 24 keV and 19 MeV are generated at the PTB accelerator facility. They are produced in a low-scatter experimental hall in open geometry using the ^{7}Li(p,n), D(d,n), T(p,n) and the T(d,n) reactions. These reactions are used at neutron emission angles Θ of 0° to produce the reference fields defined in the ISO 8592 standard (neutron energies of 144 keV, 250 keV, 565 keV, 1.2 MeV, 2.5 MeV, 5 MeV, 8 MeV, 14.8 MeV and 19 MeV).

Irradiations with quasi-monoenergetic neutrons of higher energies can be carried out using the neutron beam facilities of the Université Catholique de Louvain (UCL) in Louvain-la-Neuve, Belgium [76] and the iThemba Laboratory for Accelerator-Based Sciences (iTL) in Cape Town, South Africa [123]. Table 8 gives an overview of the field characteristics of the available calibration fields at PTB, UCL and iTL.

The specification of the fields and beams in terms of peak fluence and spectral fluence is traceable to primary standard cross sections. This provides a unique possibility to investigate the properties, especially the energy dependence of neutron dosimeters in the energy range from thermal to 200 MeV. More details are given in ref. (124).

Table 8: Summary of characteristics of available calibration fields. Monoenergetic fields ($<E_n>$ = 0.024 MeV–19 MeV): ($d\Phi/dt$) and ($dH^*(10)/dt$) in a distance of 1 m from the target. Quasi-monoenergetic fields ($<E_n>$ = 32.7 MeV–198 MeV): $<E_n>$ is the mean energy of the high-energy peak; ΔE_n is the FWHM of the high-energy peak; ($d\Phi/dt$) and ($dH^*(10)/dt$) in a distance of 6 m from the target and for a 5 mm Li target; (Φ_{sc}/Φ) is the contribution of the low-energy background to the total fluence Φ.

Reaction	**$<E_n>$ MeV**	**ΔE_n MeV**	**Target**	**($d\Phi/dt$) $cm^{-2}s^{-1}$**	**Φ_{sc}/Φ %**	**($dH^*(10)/dt$) mSv h^{-1}**	**Location**
^{7}Li (p,n) ^{7}Be	0.024	0.002	LiOH	$1.7 \cdot 10^2$	3.6	0.012	PTB
^{7}Li (p,n) ^{7}Be	0.144	0.024	LiOH	$5.0 \cdot 10^2$	2.0	0.23	PTB
^{7}Li (p,n) ^{7}Be	0.25	0.019	LiOH	$2.5 \cdot 10^2$	6.2	0.19	PTB
^{7}Li (p,n) ^{7}Be	0.565	0.015	LiOH	$1.2E \cdot 10^3$	1.8	1.5	PTB
^{3}H (p,n) ^{3}He	1.2	0.091	Ti(T)	$2.0 \cdot 10^3$	3.1	3.1	PTB
^{3}H (p,n) ^{3}He	2.5	0.127	Ti(T)	$4.9 \cdot 10^3$	1.4	7.3	PTB
^{2}H (d,n) ^{3}He	5.0	0.200	D_2-Gas	$5.2 \cdot 10^3$	<1.0	7.5	PTB
^{2}H (d,n) ^{3}He	8.0	0.200	D_2-Gas	$1.9 \cdot 10^4$	<1.0	27.5	PTB
^{3}H (d,n) ^{4}He	14.8	0.431	Ti(T)	$1.3 \cdot 10^4$	3.0	24.3	PTB
^{3}H (d,n) ^{4}He	19.0	0.300	Ti(T)	$8.5 \cdot 10^2$	1.2	1.8	PTB
^{7}Li (p,n) ^{7}Be	32.7	3.8	Li	$1 \cdot 10^5$	54	200	UCL
^{7}Li (p,n) ^{7}Be	45.3	2.1	Li	$1 \cdot 10^5$	64	200	UCL
^{7}Li (p,n) ^{7}Be	60.0	1.9	Li	$1 \cdot 10^5$	60	200	UCL
^{7}Li (p,n) ^{7}Be	97.4	1.5	Li	$2 \cdot 10^4$	60	30	TLABS
^{7}Li (p,n) ^{7}Be	148	1.3	Li	$4 \cdot 10^3$	63	4	TLABS
^{7}Li (p,n) ^{7}Be	198	1.0	Li	$2 \cdot 10^3$	65	2	TLABS

6.3.2 NPL

Monoenergetic neutron fields available at NPL cover most of the ISO recommended energies (117). They include 0.144, 0.250, 0.565, 1.2, 2.5, and 5.0 MeV. They are produced using a 3.5 MV Van de Graaff accelerator, and their characteristics are very similar to those outlined in Table 8. Irradiations are performed in a large low scatter environment which minimizes corrections for room and air scattered neutrons, although techniques such as the use of shadow cones or inverse square fits are available to make these corrections. Information is available on the contaminant target scatter components. Fluences are determined using well characterized long counters which have been validated in several international comparisons.

6.3.3 TSL

Quasi-monoenergetic neutron fields are available at TSL, Uppsala, Sweden. As outlined in Section 3.1.4, a new neutron beam facility has been taken into operation less than two years ago. The facility is in regular operation, providing beams to various users, with irradiations of electronics as the largest activity. Beams at nominal neutron energies (high-energy peak energy) of 22, 46, 75, 95, 143 and 175 MeV have been developed. For all these fields, neutron energy spectra from 5 MeV and up to maximum energy have been measured using proton recoil telescopes, and the results are available for users. Energies below 5 MeV remain to be characterized. The (non-) uniformity of the beam has been measured at 95 MeV and data analysis is in progress.

6.3.4 IRSN at Cadarache

To produce ISO standard monoenergetic neutron fields (144 keV, 250 keV, 565 keV, 1.2 MeV, 2.5 MeV, 5 MeV, 8 MeV, 14.8 MeV and 19 MeV) [117], IRSN owns three accelerators. Two neutron generators of 150 kV and 400 kV are used for high neutron fluence production at 15 MeV and 3 MeV respectively. A new 2 MV tandetron accelerator, AMANDE, is dedicated to the production of reference monoenergetic neutron fields within the energy range 2 keV–19 MeV as well as reference high-energy (7 MeV) and secondary standard gamma rays.

6.3.4.1 T400 and J25 generators

The neutron generators T400 and J25, nominally running at deuteron energies of 350 keV and 120 keV, respectively, are used to provide high neutron fluences for radiation protection applications. The targets which are used are thick enough to stop the incident charged particle beam. The neutron fluence is determined and monitored by using the associated particle method: three Si diodes, located backwards to the target (175º) allow the detection of the alpha particles (J25) or the protons (T400) emitted during the respective neutron producing reactions. The characteristics of the produced neutron fields and the maximum values of the fluence and ambient dose equivalent rates are given in Table 9.

Table 9: Characteristics of the neutron fields produced with the T400 and the J25 accelerators. The neutron energy resolution ΔEn corresponds to the FWHM of the 'monoenergetic' peak. The neutron fluence rates and the personal dose equivalent rates are maximum values, at 1 m from the neutron producing target, at 0º with respect to the deuterons beam direction [125].

Accelerator	E_d (keV)	*E*n (0°) (MeV)	ΔEn/*E*n	Neutron yield (s^{-1})	dΦ/dt max ($\times 10^4$ cm^{-2} s^{-1})	d*H*p(10,0°)/dt max (mSv/h)
T400	350	3.1	10%	2.2×10^9	3.6 ± 0.2	56 ± 3
J25	120	14.7	1.7%	1.4×10^{10}	11.8 ± 0.7	240 ± 13

6.3.4.2 The AMANDE facility

The AMANDE accelerator is a HVEE 2 MV Tandetron accelerator system delivering proton or deuteron beams in the energy range 100 keV – 4 MeV, in a DC or in a pulsed mode, with an excellent energy resolution. The neutrons are produced by nuclear interactions of accelerated charged particles (protons or deuterons) on thin targets of scandium, lithium (or lithium fluoride), deuterium or tritium in titanium. The AMANDE experimental hall is $20 \times 20 \times 16$ m^3 with metallic walls and with a floor grating placed 6 m above the ground. A full automated transport system allows the positioning of the detectors at any distance between 0.5 and 6 m from the neutron-producing target and at an angle between –160º and +160º with respect to the incident beam direction [126]. The characteristics of the IRSN quasi-monoenergetic neutron fields are given in Table 10.

Table 10: Characteristics of the IRSN quasi-monoenergetic neutron fields recommended by the ISO 8529-1 standard. The nuclear reactions, the targets used and their thickness, the energy of the incident particle and the energy of the neutrons emitted at 0º (except for those marked with *) are detailed in the first four columns. The energy resolution of the monoenergetic neutron peak is indicated in the fifth column, followed by the values of the maximum neutron yield, the neutron fluence rates and the personal dose equivalent rates, respectively, both given at 1 m from the neutron producing target. The relative contribution of the room scattered neutrons to be added and the maximum charged particle beam current are also given.

Reaction	Thickness of deposit (µg/cm²)	E_p-E_d (MeV)	E_n (0°) (MeV)	$\Delta E_n/E_n$	Maximum neutron yield (s⁻¹)	$d\Phi_{max}/dt$ (0°) (cm⁻² s⁻¹)	Φ_{sc}/Φ	$dHp_{max}(10,0°)/dt$ (mSv h⁻¹)	Φ_{sc}/Φ	I_{max} (µA)
$^{45}Sc(p,n)^{45}Ti$	5 25	2.91	0.002*	30%	1.3×10^5	2	18%	5.2×10^{-5}	19%	50
				80%	6.4×10^5	8		2.6×10^{-4}		
		2.92	0.024	2.5%	2.1×10^5	3	13%	2.0×10^{-4}	9%	
				10%	1.1×10^6	14		1.0×10^{-3}		
$^7Li(p,n)^7Be$ (target LiF)	10 40 120	1.9	0.024*	15%	1.9×10^6	15	–	1.1×10^{-3}	–	7
				24%	8.0×10^6	65		4.7×10^{-3}		
				55%	2.4×10^7	230		0.02		
		1.9	0.144	3%	2.1×10^6	55	6%	0.02	3%	
				6%	9.0×10^6	220		0.11		
				14%	2.6×10^7	670		0.32		
		2.0	0.250	1%	3.0×10^6	35	11%	0.03	5%	
				3%	1.2×10^7	150		0.11		
				6%	3.0×10^7	350		0.29		
		2.3	0.565	0.5%	3.5×10^6	100	4%	0.1	3%	6
				1%	1.4×10^7	420		0.5		
				2%	4.0×10^7	1200		1.5		
$^3H(p,n)^3He$ (target TiT)	200 800 2000	2.0	1.2	1.5%	5.2×10^7	770	7%	1.2	5%	7
				5%	2.1×10^8	3100		4.8		
				13%	5.9×10^8	8700		13.6		
		3.3	2.5	0.6%	5.1×10^7	1050	4%	1.7	3%	5
				1.8%	1.8×10^8	3800		6.0		
				4.3%	5.3×10^8	10900		17.1		
		3.6	2.8	0.5%	3.3×10^7	680	–	1.1	–	4
				1.5%	1.4×10^8	2800		4.4		
				3.5%	3.9×10^8	8000		12.5		
$^2H(d,n)^3He$ (target TiD)	200 ou 800	0.1	2.8	4%	2.1×10^6	60	–	0.09	–	30
	200	1.8	5	0.6%	1.5×10^7	560	2%	0.85	2%	8
	800			2%	6.1×10^7	2320		3.5		
$^3H(d,n)^4He$ (target TiT)	200 800 2000	0.2	14.8	1.6% (200)	3.9×10^8	3300	7%	6.5	5%	5
				2.5%	3.9×10^8	3300		6.5		3.5
		2.6	19	0.15%	1.2×10^7	180	4%	0.36	3%	6
				0.5%	4.3×10^7	660		1.3		
				1.4%	1.1×10^8	1750		3.4		

6.3.5 *EC-JRC-IRMM*

The high-intensity quasi monoenergetic neutron source at IRMM is driven by a vertical 7 MV Van de Graaff accelerator producing either continuous or pulsed ion beams. The facility has two pulsing systems:

– a fast beam pulsing generating a minimum ion beam pulse width of 2 ns and pulse repetition rates of 2.5, 1.25 or 0.625 MHz, and
– a slow pulsing system giving a minimum pulsing width of 10 µs at an adjustable frequency up to 5 kHz.

The neutrons are produced by the nuclear reactions Li(p,n), T(p,n), D(d,n) or T(d,n) giving neutron fluence fields with peak energies in the regions 0.3–10 MeV and 16–24 MeV (14–16 MeV in angle) at 0º measurement angle. The neutron spectra in the energy regions 7.5–10 MeV and 20–24 MeV are less monoenergetic. Typical fluence data at 10 cm from target are given in Table 11.

Table 11: Fluence data at 10 cm from target at IRMM

Reaction	**$<E_n>$ MeV**	**ΔE_n MeV**	**$<E_p>$ MeV**	**I_p µA**	**Target**	**Target thickness mg/cm^2**	**Neutron fluence rate at 10 cm distance cm^{-2} s^{-1}**
Li(p,n)	0.25	0.075	2.047	25	LiF	0.5	5.03×10^5
Li(p,n)	0.565	0.061	2.321	20	LiF	0.5	2.00×10^6
T(p,n)	1.2	0.05	2.022	25	TiT	2.0	3.23×10^6
T(p,n)	2.5	0.137	3.351	15	TiT	2.0	3.89×10^6
D(d,n)	5.0	0.356	1.943	25	TiD	2.0	2.82×10^6
D(d,n)	8.0	0.171	4.841	10	TiD	2.0	1.97×10^6
T(d,n)*	14.8	0.428	0.964	50	TiT	2.0	4.22×10^6
T(d,n)	16.2	1.049	0.966	50	TiT	2.0	4.62×10^6
T(d,n)	19.0	0.338	2.679	20	TiT	2.0	7.58×10^5

*Neutron fluence in 74º angle.

The laboratory houses six experimental set-ups in two large low scatter halls. The accelerator is operated 24 hours a day, seven days a week and provides a stable neutron field for more than a week without interruption. Neutron fluxes and neutron energy spectra are monitored and characterized with high precision long counters, proportional counters, Bonner spheres, time-of-flight systems, fission chambers and activation foils. Absolute neutron fluences are measured using two recoil proton telescopes which have been validated in several international comparisons. Several shadow cones are available for measurements of possible neutron scattering.

6.4 Simulated workplace fields

When selecting a workplace neutron field (designed for calibrating and testing either personal dosimeters or area monitors) one has to consider the characteristics of the field to be simulated (such as its energy and direction distributions) and the response of the instruments or dosimeters used to determine the neutron distributions. Workplace neutron fields can be simulated using three types of irradiation facilities: radionuclide sources, nuclear reactors and particle accelerators [(127)]. Since we are here interested in workplace fields around high-energy accelerators, the latter of the three methods is the only practicable one. Essentially only two facilities of this type are available in Europe: the CERF facility at CERN and CANEL at Cadarache.

6.4.1 The CERN-EU high-energy Reference Field (CERF) facility

The CERN-EU high-energy reference field (CERF) facility [128] is installed in one of the secondary beam lines (H6) from the Super Proton Synchrotron (SPS), in the North Experimental Area on the Prévessin (French) site of CERN (Fig. 39). A positive hadron beam (35% protons, 61% pions and 4% kaons) with momentum of 120 GeV/*c* is stopped in a copper target, 7 cm in diameter and 50 cm in length, which can be installed in two different positions inside an irradiation cave. The secondary particles produced in the target traverse a shielding, on top of these two positions and at 90° with respect to the incoming beam direction, made up of either 80 cm concrete or 40 cm iron. These roof-shields produce almost uniform radiation fields over two areas of 2×2 m^2, each of them divided into 16 squares of 50×50 cm^2. Each element of these 'grids' represents a reference exposure location. Additional measurement positions are available behind the lateral shielding of the irradiation cave, at the same angles with respect to the target as for the two roof positions. Shielding is either 80 cm or 160 cm thick concrete, and at both positions 8 additional exposure locations (arranged in 2×4 grids made up of the same 50×50 cm^2 elements) are provided. The nominal measurement locations (the reference field) are at the centre of each square at 25 cm above floor, i.e. at the centre of a $50 \times 50 \times 50$ cm^3 air volume, where the radiation field is calculated. The intensity of the primary beam is monitored by an air-filled ionization chamber at atmospheric pressure placed in the beam just upstream of the copper target. Typical values of dose equivalent rates are 1–2 nSv per chamber count on top of the 40 cm iron roof-shield and 0.3 nSv per chamber count outside the 80 cm concrete shields (roof and side). By adjusting the beam intensity on the target the dose equivalent rate at the reference positions can be varied from 25 µSv/h to 1 mSv/h on the iron roof-shield and from 5 to 600 µSv/h on the 80 cm concrete roof or lateral shield. The dose equivalent rate outside the 160 cm thick concrete shield is much lower and for this reason this measurement position is seldom used. The neutron energy distributions calculated with the FLUKA Monte Carlo code are shown in Fig. 40.

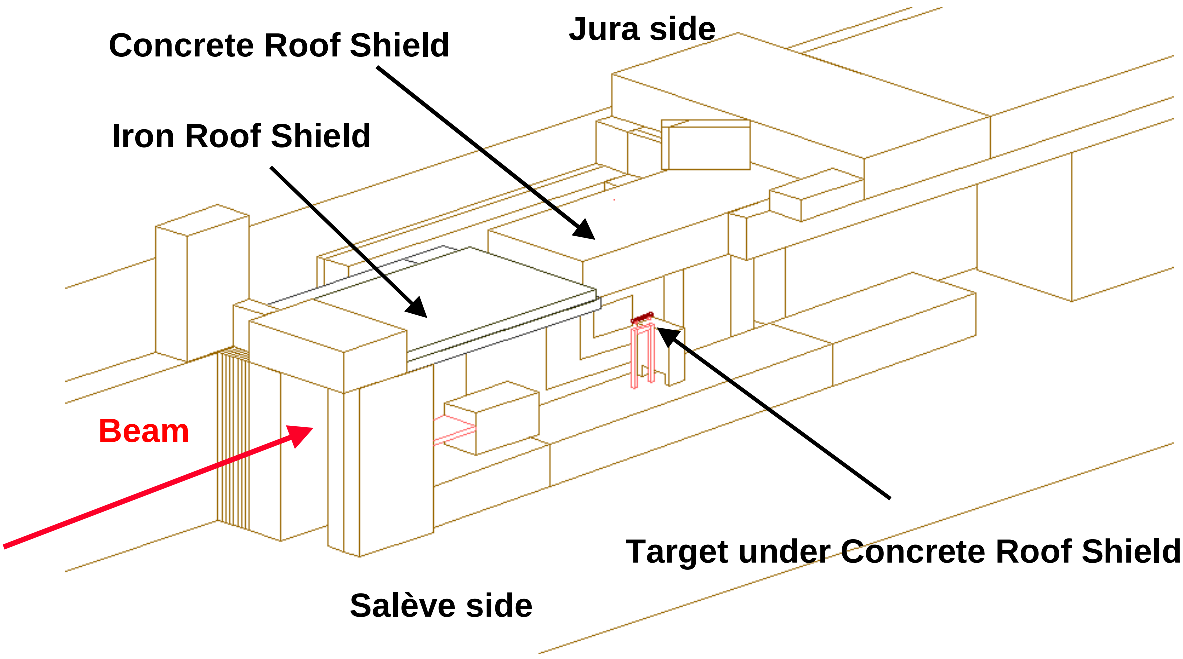

Fig. 39: Axonometric view of the CERF facility in the North Experimental Hall on the Prévessin site of CERN as modelled in FLUKA. The side shielding is removed to show the inside of the irradiation cave with the copper target set-up.

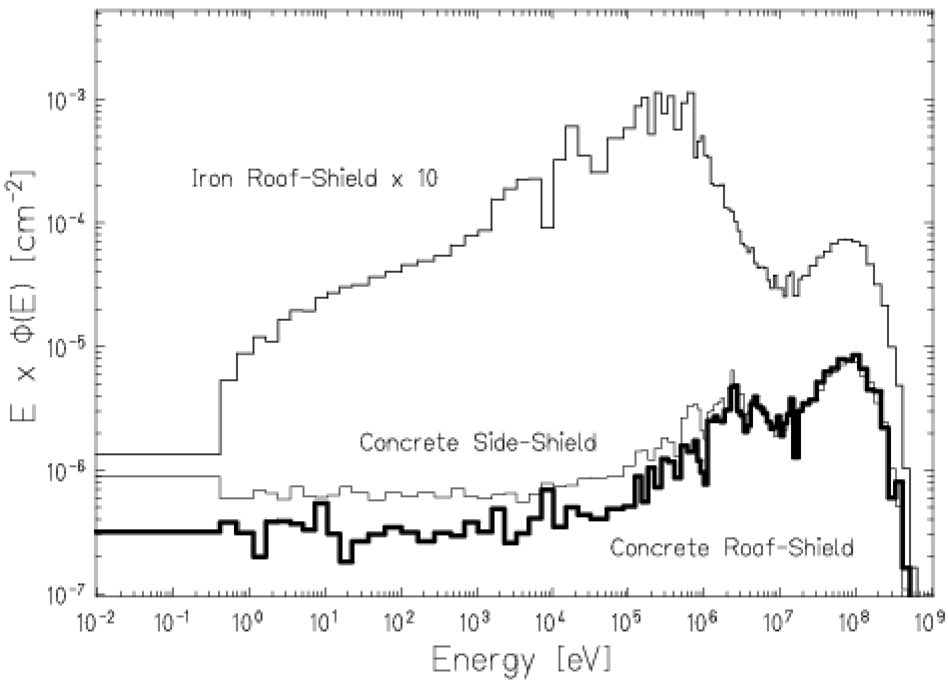

Fig. 40: Neutron spectral fluences *E Φ(E)* outside the concrete roof-shield, the iron roof-shield and the 80 cm thick concrete side-shield (neutrons per primary beam particle incident on the copper target)

The spectrum outside the iron shield is dominated by neutrons in the 0.1–1 MeV range. The energy distribution outside both concrete shields shows distributions in which this energy region is reduced while the contribution of 10–100 MeV neutrons dominates. Therefore these exposure locations provide wide spectrum radiation fields well suited to test dosimetric instrumentation under different conditions. The concrete roof shield, in particular, reproduces fairly closely the neutron field produced by cosmic rays at commercial flight altitudes. The neutron spectral fluence behind the side 80 cm thick concrete shield is similar, but presents an increased low-energy tail due to backscatter. The fluence rate of other hadrons is much lower than that of neutrons. However, an additional muon component is present which directly comes from the upstream H6 beam line and adjacent lines, as well as from pion decay in the beam line. These muons stream over the concrete and iron roof-shields. Their intensity depends on various factors which are not under direct control, such as the intensity of secondary beams in neighbouring beam lines. The accuracy of the calculated neutron spectral fluences was verified by several Bonner Spheres measurements.

Several measurement campaigns have taken place at CERF starting in 1992. Many institutions from all over Europe, as well as from the USA, Canada and Japan, have used the facility to test various types of passive and active detectors. These included devices such as TEPCs, Geiger Müller counters, different types of rem counters, bubble detectors, scintillation based dose-rate meters, electronic pocket dosimeters, Si-diodes, track etched detectors (TED), thermoluminescent dosimeters (TLD), films, nuclear track detectors, recombination chambers, multisphere systems, CR-39 foils. Although most of the beam time was dedicated to test dosimetric instrumentation, the facility has also been exploited for other uses. Experimental applications for which the facility has been used include test and intercomparison of active instrumentation and passive devices, test of active and passive dosimeters used for individual monitoring, calibration of devices before their use for in-flight measurements either on commercial flights or in space, various tests related to the LHC project, investigations of computer memory upsets and radiobiological studies. In particular all instruments and dosimeters used for on-board measurements in the framework of various EU funded programmes have been periodically tested and calibrated at CERF. Recent applications include tests on instrumentation for the RAMSES project (see Section 5.3), activation experiments on various materials in order to benchmark the capability of Monte Carlo codes to correctly predict induced radioactivity and dose rates [(129)], and test of high-level dosimeters.

6.4.2 The CANEL facility at Cadarache

CANEL is a modular assembly which can be coupled with the neutron generators, so called J25 and T400 (see Section 6.3.4.1) to produce realistic neutron fields [(127)]. The CANEL assembly was designed to produce simulated workplace neutron fields comparable to some of those encountered at workplaces, in particular at nuclear power plants. High-energy neutrons are converted by a depleted uranium shell producing fission neutrons, which are in turn moderated by iron, water and polyethylene (Fig. 41). This assembly is positioned around the deuterated titanium target of the T400 accelerator (or TiT target of the J25 accelerator – producing 14.7 MeV neutrons) producing the 3.3 MeV original neutrons.

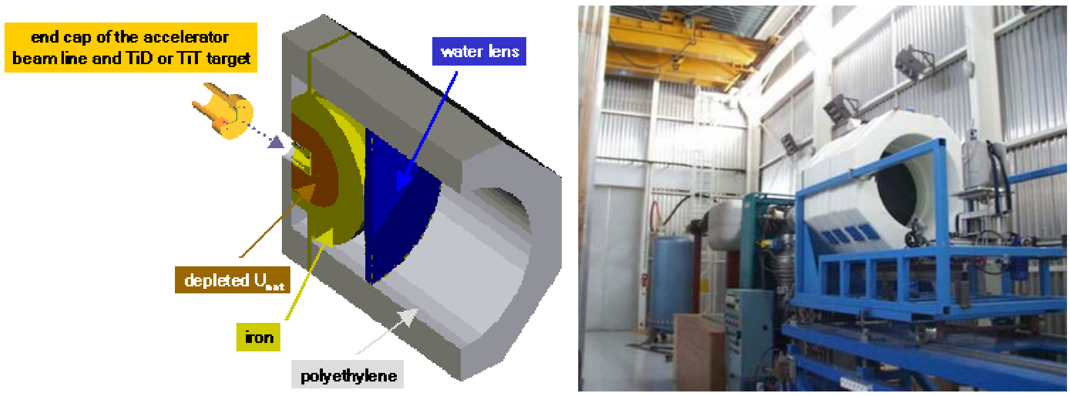

Fig. 41: Photograph and scheme of the CANEL assembly coupled to the T400 accelerator

The neutron fluence energy distributions at positions where calibrations are usually performed are shown in Fig. 42. These distributions were determined both experimentally and by Monte Carlo simulations. The maximum values of the neutron fluence rates and the ambient dose equivalent rates at the calibration positions and the relative contributions per energy group are given in Table 12.

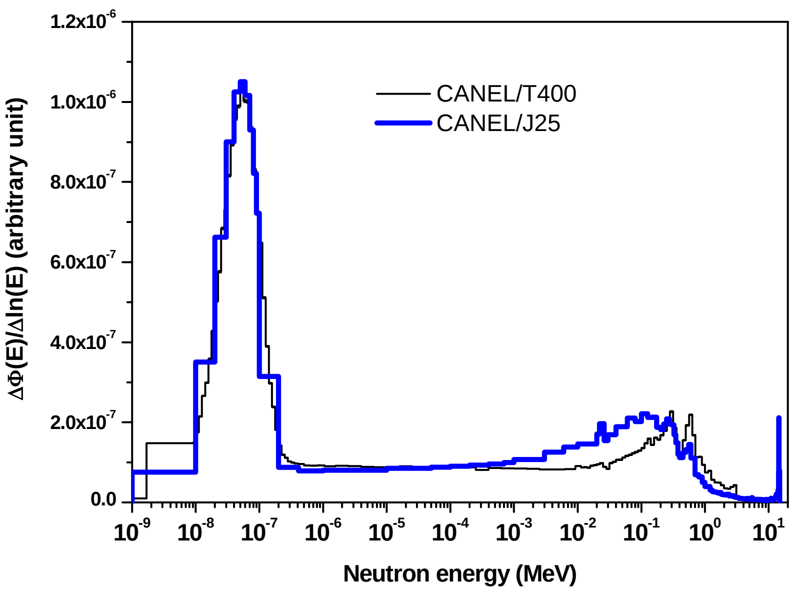

Fig. 42: Neutron fluence energy distribution at CANEL, used with the T400 and the J25 accelerators.

Table 12: Neutron fluence and ambient dose equivalent rates of the CANEL/T400 and CANEL/J25 facilities [125].

	E_n (MeV)	**Total**	**$10^{-11} \leq E_n < 5\times10^{-7}$**	**$5\times10^{-7} \leq E_n < 10^{-1}$**	**$10^{-1} \leq E_n$**
CANEL/T400	$\dot{\Phi}_n$ ($cm^{-2}\,s^{-1}$)	8150 ± 350	56.0%	25.2%	18.8%
	$\dot{H}^*(10)$ ($mSv\,h^{-1}$)	*1.32 ± 0.07*	*15.5%*	*4.9%*	*79.6%*
CANEL/J25	$\dot{\Phi}_n$ ($cm^{-2}\,s^{-1}$)	262000 ± 9000	54.7%	31.0%	14.3%
	$\dot{H}^*(10)$ ($mSv\,h^{-1}$)	*31.7 ± 4.1*	*16.5%*	*10.2%*	*73.3%*

7 Conclusions

This report has reviewed the principal techniques, based both on active detectors and passive dosimeters, employed to monitor mixed radiation fields around high-energy particle accelerators and experimental thermonuclear fusion reactors. Neutron measuring devices included rem counters, Bonner sphere spectrometers, bubble detectors and track etched detectors. Techniques discussed for photon dosimetry and spectrometry were scintillation detectors, ionization chambers, Geiger Müller counters, TLDs and EPR dosimeters. Instruments capable to distinguish between the low-LET and high-LET components of a field like TEPCs were also discussed. Secondary (stray) radiation often keeps “memory” of the original time structure of the primary beam, and if the beam is made up of very short bursts, the influence of such structure on active instruments has to be properly taken into account when selecting or designing a monitoring system. This aspect has been addressed in some detail in this report.

The characterization of the neutron field produced at high-energy proton accelerators is quite a challenging task. Developments occurred over the past few years to improve the response of neutron counters and spectrometers beyond 20 MeV have been discussed.

Instruments and dosimeters used for workplace monitoring usually do not have ideal response characteristics, i.e. the same energy dependence as the fluence-to-dose equivalent conversion function. They are normally employed under irradiation conditions that are different from those in which they were calibrated. Thus deviations will occur and proper correction factors have to be applied.

The response of a device to the various components of a mixed radiation field can nowadays be determined quite precisely by means of Monte Carlo codes. It is nonetheless important that the simulations are validated with calibration measurements in monoenergetic or quasi-monoenergetic reference fields. It is also important to be able to calibrate a dosimeter in a simulated workplace field produced under laboratory conditions with particle compositions and spectral fluences similar to those encountered at the workplace of interest. Such a field offers the opportunity of investigating the dosimeter characteristics and of intercomparing different dosimeters under identical and reproducible conditions.

There are a number of issues that still need to be better understood, such as the problems arising from calibration for high-energy devices, for instance rem counters with a lead insert which are also sensitive to low-energy neutrons. For neutrons above 20 MeV only ‘quasi-monoenergetic’ fields are available, i.e. fields with a major component at one energy, but with an additional broad energy component, usually at lower energies, for which corrections have to be made. In addition, the quasi-monoenergetic neutron fields above 20 MeV are not regularly available for ‘routine’ calibrations. There is also a certain need of better estimating uncertainties in conversion coefficients.

It has been mentioned in the beginning of this report that the basic protection quantity is the effective dose *E*, but that for purposes of radiation protection metrology the operational quantity ambient dose equivalent, *H**(10), is used, which is meant to be a conservative approximation of *E*. Recent studies (79, 130, 131) have shown that in some circumstances the operational quantities may not always provide an overestimate of protection quantities, so that future developments in instrumentation will have to take this fact into account.

Acknowledgements

The authors wish to thank the following colleagues for providing valuable information included in this report: G. Arduini, D. Perrin and M. Rettig (CERN, Switzerland), D. Bartlett (HPA, UK), G. Datzmann and J. Hauffe (RPTC, Germany), S. Delacroix (ICPO, France), G. Lövestam (JRC Geel, Belgium), K. Ott (BESSY, Germany), B. Rannou (GANIL, France), S. Rossi (CNAO, Italy), D. Thomas (NPL, U.K.), G. Tromba (ELETTRA, Italy), F. Trompier (IRSN, France). Thanks also to H. Schuhmacher (PTB, Germany) for his careful reading of the manuscript and useful comments.

This work is funded in part by the European Commission under the auspices of the Euratom 6th Framework Programme for research and training in nuclear energy, Contract No FI6R-012684.

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