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Interner Bericht
DESY D3-75
September 1993

The Radiation Protection Group of the Deutsches Elektronen-Synchrotron DESY 1963 – 1993

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To be published as part of a forthcoming book on the history of radiation protection at accelerators.

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Contents:

1. The Early Days and the First Shielding Experiment

The first DESY staff commenced work in 1957. A 6 GeV electron synchrotron was planned with a 40 MeV linear accelerator as injector. Both accelerators were modelled upon the 6 GeV CEA electron synchrotron in Cambridge/Massachusetts. Just like the CEA, DESY was constructed on an open space of 0.4 km² area within the confines of a large city. Nowadays one would not select such a location but at that time there was no sign of animosity from the local populace concerning new nuclear facilities. In the early years there was no radiation protection group. The theorist Cord Passow, who was mainly involved in determining the accelerator parameters and the problems concerned with beam measurements, specified the shielding. It is still of interest to read his notes from 1958. Not much more than general properties of high energy electrons and photons were known, together with Panofsky's number of neutrons produced from 6 GeV electrons and the "skyshine theory" proposed by Lindenbaum in 1957 after the bad experience from the shielding of the Bevatron and the Cosmotron. The resulting 2.5 m thick sand shielding over the synchrotron would nowadays still be accepted, although the most penetrating radiation component (high energy neutrons) were not considered at that time. Apparently one can reasonably shield a high energy accelerator with a minimum of information and a certain amount of luck. Both the large experimental halls were surrounded by high sand walls. The teams were assumed to remain outside the halls whilst running the experiments.

In 1963 – one year before the synchrotron started operation – Eberhard Freytag and Klaus Tesch joined the staff to be in charge of radiation protection. The group leader was Günther Bathow who was also responsible for the construction of the vacuum chamber for the synchrotron. Klaus Tesch was a nuclear physicist, Eberhard Freytag came from solid state physics and both knew nothing about radiation protection.

Hence Klaus Tesch was sent for several months to CERN – at that time the largest accelerator facility – in order to become familiar with the basics of radiation protection and the measuring methods. This visit turned out to be very helpful and fruitful for DESY. At that time Johan Baarli, Klaus Goebel, Tony Sullivan and Alessandro Rindi were working in the radiation protection group at CERN – names known to all in our field of work. The friendly collaboration with this group originates from these early days. We had one year in which to obtain the most important measuring instruments; neither engineers nor technicians were available to us at that time. We used the usual portable instruments known in nuclear physics and conventional dosimetry together with activation probes and their evaluation instruments. In order to monitor the site a large number of argon-filled ionisation chambers were purchased from the company PTW Pychlau. These chambers were quite unique: the ionisation current was applied without amplification to a condenser, which on reaching a certain potential was then discharged through an electrostatic relay. The discharge pulses from all chambers were recorded in a central control room. The sensitivity even without any electronics was so high, that each pulse was equivalent to a dose of 1 μSv. However, the relay mechanism had to be frequently adjusted. The central electronics were connected to the accelerator's interlock system. If a certain dose rate was exceeded the accelerator would be automatically switched off – a precaution that has been retained up to the present day.

The synchrotron commenced operation in February 1964 when a beam energy of 5 GeV was achieved. In the following month the first external beam, a 4.8 GeV bremsstrahlung beam, was brought into one of the experimental halls. With this beam we were able to carry out a shielding experiment (Ba 64) as the first DESY experiment. The beam ended in a quantameter whose concrete shielding could be altered laterally and at small angles. The equipment used comprised ionisation chambers filled with argon, tissue-equivalent ionisation chambers according to Rossi and Failla, ^{6}LiI scintillator or indium foil in a moderator and phosphorus as an activation detector. Despite the many teething problems with the operation of the synchrotron we were able to determine the dose absorption curves of the e-γ component and of neutrons as well as the number of neutrons produced per equivalent γ-quantum. And we were proud when in January 1965 Herbert De Stabler, Jr., wrote from the famous SLAC laboratory in Stanford: *"I think it is clearly the best shielding experiment done at an electron accelerator"*.

The following points arose as a consequence of this experiment which were of importance for the future of the radiation protection group:

- It was a good example of the high priority allocated to safety, especially radiation protection, compared to that for the experiments and the development of the accelerator. Indeed the radiation protection group physicists were given the right to issue directives to all other DESY workers in matters of radiation safety.
- There was always sufficient financial support for equipping the group with instruments.
- Radiation protection experiments which are intended to achieve fundamental results require the availability of main-user beam time.
- The experiment showed the way for both the future activities of the group: shielding experiments and the development of dose measuring equipment.
- It especially showed that external beams in the experimental halls are best shielded with movable concrete blocks as at other large accelerators: it turned out that the walls of sand piled up around the halls were superfluous.

The philosophy described here in brief has proved its worth at DESY up to the present day. It has avoided disagreements concerning competency in questions of safety. There have been no cases of over-exposure or radiation accidents. (Only in one single case could over-exposure not be excluded for a worker on a facility for cavity testing). However, the radiation protection group has always been one of the smallest groups with respect to its staffing level. Günther Bathow and Eberhard Freytag left the group in 1971 in order to work on the development of new accelerators. As replacement Herbert Dinter joined the group – he had previously been involved in research. Klaus Tesch was appointed to the position of group leader. Two engineers and three technicians provided support – this composition has remained unto the present day.

The following is intended to show the developments in both the above-mentioned areas of work. The most important papers published in journals are listed at the end since they can be regarded as representing the milestones of our work. Since we wish to concentrate upon the contribution made by the DESY group towards the general development of radiation protection at accelerators we will not quote other works in the present review. It will however become clear that without the suggestions, results and direct help from colleagues from other laboratories many of the results would not have been possible.

2. Developments in Instrumentation

Our first commercial equipment was described in the previous section. The instruments for measuring neutron doses were rather impractical for daily use and often too insensitive in the neutron fields behind shielding. Thus is was a considerable step forward when in 1965 the neutron dose meter according to Andersson and Braun (the so-called Rem Counter) appeared on the market. This instrument is even today the most important neutron dosimeter. We purchased the first available models which are still in use today.

In contrast to conventional dosimetry, usage at high-energy accelerators places special requirements on the dosimeters. Firstly, the measuring range of a usual neutron dosimeter, which extends from thermal energy to around 15 MeV in case of the Rem Counter, is insufficient for registering neutrons up to 150 MeV. We know now (see Section 4) that behind the concrete shielding of a proton accelerator the main component of the neutron dose is due to about 70 MeV neutrons. Secondly, the dosimeters must work correctly in pulsed fields. Our work on dosimeters at the beginning of the 1970s was concerned with both these problems.

The oldest and best known method for measuring the neutron dose above 20 MeV is the activation of a plastic scintillator by the reaction $^{12}C\ (n,2n)^{11}C$, which we of course also employed. Due to ^{11}C having a half life of 20 minutes it can only be used in special cases and not for site monitoring. For longer term measurements we suggested (Te 70) to use a scintillation counter with plastic scintillator 5 cm ø by 5 cm. One can show that the correct response curve for neutrons above 20 MeV is received when the threshold of the pulse counter is suitably chosen so that the instrument can be calibrated as a dose meter. The pulses due to electrons have to be suppressed by means of pulse shape discrimination. A further method for the dosimetry of high energy neutrons is to surround a detector for thermal neutrons with an especially thick moderator. We employed a 45 cm polyethylene sphere with a ^{3}He counter in combination with the Rem Counter.

Neither of the instruments described are really practicable for routine measurements. However we have performed numerous measurements with them and have found that the high energy neutrons behind the shielding of our electron accelerators approximately double the neutron dose measured solely with the Rem Counter. Since the neutron dose at electron accelerators does not play a significant role anyway, we subsequently just used the Rem Counter and multiplied the measured results with an appropriate safety factor as an approximation.

The problem of dose measurements in pulsed radiation fields seemed more serious to us. Such a situation arises for example when an electron beam is ejected out of the synchrotron in "fast" mode of operation. Moderating neutron counters are usually equipped with proportional counters which exhibit a certain dead time. It is true that thermal neutrons are "stored" for a while within a moderator but the exact time behaviour was unknown. To investigate this effect we generated a very short (1 μs) pulse with our linear accelerator and measured the time distribution of the pulses for various moderating neutron counters (Di76). With this distribution and some calculations one can determine the counting losses for any neutron field of given time structure. We were pleased to find that our experimentally determined distributions were confirmed by calculations 17 years later. Vjacheslav Kryuchkov from the IHEP institute in Protvino informed us recently that his solution of the time dependent transport equation for polyethylene spheres was in good agreement with our curves.

Earlier we had been involved with the behaviour of ionisation chambers in pulsed fields since we had employed large numbers of argon filled chambers for site monitoring. In a chamber the ion concentration can be represented by a solvable Ricatti differential equation taking into account removal of ions and recombination (Di74). In this way one can calculate the recombination losses in pulsed fields as a function of the high voltage of the chamber. The calculations were again verified by means of measurements at our linear accelerator where the dose measured by the chamber was compared with the dose from solid state dosimeters.

We considered this work to be important since we employed both ionisation chambers and Rem Counters (with $^{10}BF_3$ G.M. counters) for site monitoring. In the case of the chambers the above-mentioned electrostatic relay was soon replaced by a modern Mosfet circuitry. The monitoring of the site steadily increased in volume. The linear accelerator Linac 2 (600 MeV electrons or 400 MeV positrons) commenced operation in 1969. In 1973 the electron positron storage ring DORIS (2 × 5 GeV) and in 1978 the PETRA storage ring (2 × 23 GeV) with a circumference of 2.3 km followed. Therefore it was opportune that the thermoluminescence dosimetry in the early 1970s had reached a high degree of reliability and that commercial instruments were on the market. We have employed this method for the site survey since 1972. It was not necessary to carry out our own developments, however the properties of TL dosimeters such as dependence upon heating temperatures, reproducibility, linearity, measuring ranges, annealing, background and fading was studied in detail over the years. For monitoring neutron doses with the usual ^{6}LiF-^{7}LiF dosimeter pairs we used a cylindrical moderator 15 cm ø × 15 cm which is cheap and easy to transport. However, due to its improper response curve in the neutron energy range of interest, it is not thick enough to be used as a tissue equivalent instrument. Thus the equipment must be calibrated in the actual neutron field – we performed the calibration with the help of a Rem Counter behind various shieldings and were able to determine a mean dose calibration constant.

We also employed a further method of solid state dosimetry which is based upon the radio-photoluminescence of silver phosphate glasses. The reading instrument was purchased from Toshiba in 1968 and has been used up to the present day (with frequent repairs). In the beginning the glasses were also used for site monitoring, subsequently they were exclusively used for measuring high doses. For this area we developed the method further. We were able to show (Fr71) that not only the part of the sensitivity curve increasing linearly with dose can be exploited but also the falling part due to increasing darkening of the glass. In the region around 500 Gy both branches combine so that radio-photoluminescence do not give unique results. However, it is just this region where glasses exhibit thermoluminescence so that by employing both effects a single dosimeter can be used to measure doses between 0.01 and 10^7 Gy (Te84). This method has been very successfully used for monitoring of radiation damage or the measurement of background at storage ring experiments.

Naturally there were also numerous monitoring tasks which were dealt with by using conventional measuring equipment. An example is the determination of radionuclides in the air of accelerator rooms and the measurement of activity concentrations; these measurements and the permanent monitoring of exhausts were carried out by Klaus-Peter Klimek. In order to analyse activated objects we received a high resolution γ spectroscopy. In general the unintentional activation at electron accelerators is small compared to that at proton accelerators. Despite this we had significant problems in the 1970s with activation and radiation damage at the synchrotron during long periods of operation with currents up to 50 mA necessary to supply the fixed-target experiments with electron and photon beams. We had a lot of work to do with controlling the handling of activated materials. This problem was much reduced when DESY moved over to performing only storage ring experiments. The monitoring of machine waste from working with activated material has always been an important task, if only from the psychological point of view. Subsequently we were able to publish quantitative results for the dose due to inhalation when machining activated objects (Te91a).

The above-mentioned equipment was unexpectedly used in the beginning of May 1986, a few days after the Tschernobyl reactor disaster. To our surprise we were able to detect radioactivity in rain water, on the ground and in plants, and we could quantitatively analyse the nuclides. Since in the first days our public authorities and the official measuring boards were completely overcharged, we were the only institute that was able to inform the population of Hamburg over the (relatively low) level of radiation. In great haste we presented our results of measurements, explained the differences between Rem, Sievert, Becquerel, and so on. Many thousand copies of this simple compilation had to be made by our printing office and it became the most widely read work of our radiation protection group!

An upheaval in our work came in 1979 when the planning for the HERA storage ring commenced (820 GeV protons colliding with 26 GeV electrons). Hence we were confronted with proton accelerators on the site. It was clear that the above-mentioned dose measuring problems, i.e. the dosimetry of higher energy neutrons and the dosimetry of pulsed radiation, would be intensified. Short and irregular losses of stored beams or beam loss during injection from one accelerator into the next requires in practice the dosimetry of single pulses of radiation whose duration is in the order of 1 μs. Our Rem counters fail in this environment and also ionisation chambers can only be employed with caution. However we had sufficient time to care for suitable measuring equipment before the first operation of the proton injector. A 50 MeV linac (Linac 3) was built as injector and an additional proton synchrotron DESY 3 (7 GeV) was constructed in the synchrotron tunnel. The PETRA storage ring was modified so that in addition to electrons, protons could also be accelerated up to 40 GeV.

Considering the monitoring of the site doses we decided to use the active instruments only as radiation monitors and to perform dose measurements only with passive solid state dosimeters. Thereby it was no longer possible to automatically switch off the accelerators when a specific dose level was exceeded. However, for our well-shielded synchrotron and for the storage rings this sort of automatic system was not necessary. As a consequence, our thermoluminescence dosimetry was extended whereby the newest equipment from the Harshaw company came in very useful from 1988.

The problem of dosimetry of high energy neutrons seemed to us to present more serious problems. Of course we acquired improved equipment for the evaluation of activated plastic scintillators (^{11}C measurements). However, not enough was known about the neutron spectrum behind a shield. Thus we concentrated our efforts on the spectroscopy of neutrons produced by accelerators. The only reasonable method here is to use the well-known "Bonner spheres" which are a set of polyethylene spheres of different diameters equipped with detectors for thermal neutrons. The sensitivity curves for the spheres can be taken from the literature. From the measurements obtained by the detectors and from discrete values of the sensitivity one obtains an (under-constrained) equation system for the spectral distribution of neutrons. The spheres were equipped with the proven thermoluminescent dosimeters (^{6}LiF and ^{7}LiF) since this was the only way to obtain reasonable results in a pulsed and non-repetitive radiation field. The energy range of the largest sphere appeared to be somewhat too low since neutrons up to and above 100 MeV were to be registered. Thus we added two fission fragment detectors to the Bonner spheres. These consisted of thorium (threshold 2 MeV) or bismuth (threshold 50 MeV) in contact with Makrofol plastic foil. The etching of the plastic foil and the counting of the fission tracks were developed to a routine method by Brunhilde Racky. Computer programs for unfolding the neutron spectrum from the measurements were obtained from various authors, whereby the program LOUHI proved to be the best. We used the described spectrometer in 1991 to determine the neutron spectrum at numerous positions behind the shielding of the DESY 3 injector (7 GeV protons) and at PETRA (7 – 40 GeV) (Di92). We were able to show that neutrons between 0.1 and 150 MeV contribute to the dose whereby 2 peaks at 1 MeV (evaporation neutrons) and 70 MeV (spallation neutrons) are noticeable. In the following sections we will report on comparisons between these measurements and calculations and on further measurements at higher primary energies.

The spectrometer is of course much to complicated for the monitoring of the site where there are between 50 and 100 measuring points. For this purpose we employed only a subset of the total spectrometer detectors. Currently we use the combination of a 15 cm cylinder with LiF and the thorium fission fragment detector or just the 30 cm sphere, these instruments are cheap and can be manufactured in large numbers. Other combinations are also possible. Since they are part of the neutron spectrometer detector family it is easy to calibrate them in the actual radiation field.

Following completion of the development of solid state dosimeters for neutron dosimetry we have been recently involved again with active detectors. We had previously mentioned the scintillation counter with pulse shape discrimination as a dosimeter for high energy neutrons. This electronic method is too complicated for routine use. We attempt to achieve the discrimination against electrons by suitably dimensioning the scintillator and using a certain pulse counter threshold. Further our interest is focused again upon the Rem Counter, especially after A. Ferrari et al. showed that the instrument's range of measurement can be easily extended to above 100 MeV neutron energy. We took up an old idea of Miguel Awschalom and replaced the $^{10}BF_3$ counter by a β-GM counter wrapped in silver sheet in order to utilise the activation of silver by thermal neutrons. From the pulse difference between a counter wrapped with silver and a counter wrapped with tin the dose from an arbitrarily short neutron pulse can be reliably measured. A further possibility to avoid counting losses is to substitute the $^{10}BF_3$ counter by a fast silicon detector. These experiments are continuing.

Of course neutron dosimetry is not the only problem that the HERA project posed. One example is the measurement of the residual radioactivity along the accelerator after shut down. In principle it is a simple monitoring task which is made difficult by the sheer size of the ring (6.3 km). Klaus-Peter Klimek solved this problem by combining a small portable dosimeter with a data collection device. The latter states in plain text at which points of the ring the dosimeter's pulse rate is to be recorded by pushing a button. Back in the laboratory the data are sorted with the help of a PC and the information is printed out for the HERA crew.

Finally we should mention that we have not participated in the development of a personal neutron dosimeter for neutrons; a particularly difficult problem. In the early days we used the well known nuclear emulsions which were issued by an official monitoring office and subsequently evaluated. However, we never succeeded in measuring a relevant personal neutron dose (the unsolved fading problem may have contributed to this negative result). For this reason we ceased carrying out these measurements in 1975 and relied completely on our local dosimetry. Only when the proton accelerators commenced operations did we again start to employ the film dosimetry. We are glad to obtain the films now from the CERN radiation protection group where Manfred Höfert has the most experience with this method. Here the emulsions are sealed within dry nitrogen in order to minimise the fading. It is intended that a calibration constant be obtained by comparison with the results from the neutron spectrometer.

3. Shielding Experiments and other Measurements

During the routine monitoring of radiation there is often the opportunity to take detailed measurements of the various radiation components behind shielding. However it is usually the case that the geometries of the source and shielding are poorly defined and that the loss of primary particles is poorly known or completely unknown. The results are then valid "for typical accelerator operations". For a shielding experiment, where the shielding parameters and material constants are to be quantitatively determined, a number of conditions must be fulfilled. The size of the target must be known, the intensity of the impinging primary beam must be measurable, the geometry of the shielding must be simple and the material uniform. In practice this means that the radiation protection group has to be the main user of the beam. One does not find many such experiments in the literature and this is the main difficulty to developments in our field of work. In the following we will briefly sketch the measurements that we have carried out, since they have always been important milestones for us in the historical development of our work.

The first experiment has been described in Section 1. It took place at a bremsstrahl of low intensity, the concrete shielding had a maximum thickness of 1.2 m and we were only able to measure the two most important components: the electron-photon component and low energy neutrons. In 1966 the first electron beam was brought into an experimental hall and hence we had to deal with the most penetrating components, the high energy neutrons and muons, produced at small angles to the primary beam (Ba67a). The comprehensive work by Ralph Nelson concerning muon shielding appeared two years later and so data concerning the photo-production of this component were urgently required. In our experiment the electron beam was directed into a Faraday cup in order to measure the intensity, and the shielding in beam direction comprised heavy concrete 2-4 m thick. The high energy neutrons were detected by the ^{11}C method; for higher thicknesses we were only able to measure the low energy neutrons that were in radiation equilibrium with them. The resulting parameters for the neutron shielding matched the values that were already known for lower energies and the results of the muon measurements were compared with the contemporary calculations of Clement and Keßler.

Also in 1966 we carried out our skyshine experiment for comparison with Lindenbaum's theory and to determine its parameters (Ba67b). The DESY leadership was also interested in these measurements due to the location of our site within the confines of the city of Hamburg. At that time there was much discussion concerning the neutron back-scattering from the atmosphere, and its significance for radiation protection was certainly over-estimated. In one of the experimental halls we positioned a free-standing thick target without shielding, the hall was well secured, the radiation monitors disabled and a 4 GeV electron beam directed onto the target during a night shift. In a detection vehicle we determined the low energy neutron dose up to a distance of 600 m. It is probable that such an experiment would nowadays not be carried out on grounds of safety.

The most important component for us at electron accelerators is the electromagnetic cascade. We studied in detail their properties in 3 experiments. In 1966 we measured quantitatively for the first time in the GeV range the distribution of the cascade in a thick target of lead, copper or heavy concrete (Ba67c). Since we had no solid state dosimeters available we used a very small ionisation chamber (0.03 cm^3) remotely controlled in the slabs of the target. Three years later we were able to employ glass dosimeters and measured precisely the lateral spread of the cascade (Ba70). The dosimeters were inserted into small holes in the otherwise compact block and hence did not disturb the distribution; their large measuring range permitted the determination of the deposited energy over a range of 10^6. An important application of these results was the comparison with a Monte-Carlo program written by Uta Völkel, the fore-runner of the well-known EGS program. In general there was very good agreement, only in the fring areas (>6 Molière units) did the calculations underestimate the dose.

Whilst involved in these measurements we also obtained data concerning the photo-production of low and high energy neutrons in an optimum target. This is a target in which the maximum number of neutrons are produced whereas their attenuation within the target can be ignored. For the detection of low energy neutrons up to around 25 MeV we used indium activation probes with paraffin moderators and phosphorus. Higher energy neutrons were detected by the reaction $^{23}Na(n, 2p4n)^{18}F$ which is a rarely used activation reaction. In order to avoid unwanted spurious reactions we selected sodium peroxide Na_2O_2 as a measuring probe, a substance which is none too pleasant to handle. This finally became apparent as red phosphorus, sodium peroxide and water accidentally came in contact with each other which at a stroke gave our laboratory a rather different appearance. Apart from this setback, our measurements were successful and we obtained production rates and angular distributions for both neutron groups which were in agreement with simple estimates.

The end stop geometry of a thick target, in which most of the beam energy is absorbed, is not the most important geometry for shielding calculations. A more frequent case is that a beam strikes a magnet or the thin vacuum tube, the resulting scattered e-γ radiation produced at large angles then has to be shielded. In 1977 we obtained the necessary data in a further shielding experiment (Di77). For this experiment we were able to use the ^{7}LiF thermoluminescence dosimeters. We obtained production rates and angular distributions for various target geometries and shielding parameters for the most important materials.

The beam time that had been made available to us for the 3 experiments had paid for itself. With the collected data we were able to calculate practically all the photon doses that occurred – at least so we believed until in 1980 the PETRA e^+e^- storage ring achieved beam energies above 16 GeV. At these energies the synchrotron radiation produced by the circulating beams is not just a phenomenon of accelerator physics. The production of this radiation had of course been taken into consideration and the vacuum chamber had been shielded with lead sheets. However, this shielding was not optimal and multiply scattered synchrotron radiation entered the tunnel and to some extent was transported along the straight sections of the tunnel into the experimental halls. Considerable radiation damage occurred in the tunnel as the beam energy was further increased from 19.6 GeV to 22.4 GeV between 1982 and 1984. We had initially not been involved with synchrotron radiation since these low energy X-rays were not of interest to us. We had to correct this omission. In the next section we report on the dose calculations. Our dosimetry with silverphosphate glasses was especially suitable for measurements. Numerous readings were taken between 1982 and 1984 in order to study the dose distribution along the vacuum chamber within a dipole magnet and also within the entire tunnel cross-section. All values were normalised to a certain circulating charge and hence could be quantitatively compared with calculations (Di82, Di85).

With the help of the measurements described and a summary of theoretical works (see Section 4) we were able to calculate the doses occurring behind the shielding of electron accelerators due to the various components of high energy radiation and due to synchrotron radiation to sufficient accuracy. The solution to one problem still eluded us: the attenuation of neutron and photon doses along the access labyrinths which lead to the accelerator rooms. This was not an urgent problem. At most accelerators the labyrinths are built according to construction considerations rather than based upon quantitative dose calculations. However, we considered it to be quite useful to study the distribution of the dose due to both types of particles as a function of length and cross-section of the individual sections of the labyrinth. In both cases we proceeded in the same way. First of all we constructed typical labyrinths and ducts with concrete blocks on a car park and measured the doses from isotopic neutron sources and γ sources. We were able to verify the received dependencies of the doses upon various parameters with those at existing labyrinths and passages at our accelerators. The results were summarised in simple formulae for use at future accelerators (Te82, Te87).

Finally we should briefly mention experiments that had nothing to do with radiation protection. They involved somewhat exotic subjects in the field of elementary particle physics with which our serious experimental research groups wanted nothing to do with. In 1968 Professor de Carvalho (Brasilian Research Centre, Rio de Janeiro) visited DESY. He reported that in collaboration with a team of Professor Salvetti (Rome university) he had measured very high (γ,n) cross-sections of medium-heavy nuclei at a 1 GeV electron accelerator which could not be explained by any theory. Although this information was received with scepticism it was suggested that we should check these measurements in the 1-6 GeV range with the help of an activation method. We selected a carefully collimated bremsstrahlung beam and together with the Italian colleagues found completely normal cross-sections just as expected. We had scarcely published this result when a paper appeared in Nuclear Physics in which B. Forkman et al. also reported on large cross-sections measured at the Lund accelerator in Sweden. We were beginning to doubt the DESY results until intensive discussions revealed that the high cross-sections were due to a contamination of the bremsstrahlung beam by low energy photons (Ca69). This episode stimulated collaboration with Rome and Rio de Janeiro and also with the institute in Lund. We determined cross-sections for various photospallation and photofission reactions in the range 1-6 GeV and total cross-sections for the photo-production and electron-production of pions for energies between 130 and 580 MeV (at our linear accelerator Linac 2) (An72, Bl76, Bl77, Ca75). A method was proposed for obtaining the cross-sections per photon from the usual (non-physical) cross-sections per equivalent γ quantum by a computational unfolding and for estimating the errors (Te71).

Of course we have also tried to win a Nobel prize. After the quark hypothesis appeared in 1964, A. Zichichi suggested further hypotheses that perhaps also electrons could be built from quarks, so-called leptonic quarks. Whilst today these ideas appear to be rather nonsensical we were asked to look for such particles. In a relatively large counter experiment we searched for particles with 1/3 and 2/3 elementary charge behind the shielding of a 6 GeV electron beam (Ba67d). It is well known that we did not acquire a Nobel prize but the experiment did have one advantage: our group received modern nanosecond electronics which proved to be of good value in the following years.

4. Theoretical Work

The physicists belonging to a radiation protection group at an accelerator are usually experimental physicists – radiation protection is above all involved with measurements. On the other hand they also have the task of specifying the necessary shielding for new accelerators or higher beam energies. It is interesting to use the example of the DESY radiation protection group for following the way in which the methods for dealing with this task have developed over 30 years.

In the early years our shielding considerations were based mainly upon a thorough study of the relevant literature. All published works were examined to see if they could be extrapolated and applied to the current problem. Of importance were also internal reports on more or less successful work, which are exchanged between the various laboratories as part of good international collaboration. The first results obtained from Monte-Carlo calculations, which arose from the needs of experimental high-energy physics, could be used. There was often sufficient material to enable simple rules or formulae to be extracted from the scattered information, which were also of general interest and described the contemporary state of knowledge.

The first summary of this sort was the pocket book by Eberhard Freytag concerning radiation protection at high-energy accelerators (Fr72). It appeared a year before the comprehensive publication on the same subject by Wade Patterson and Ralph Thomas, and since written in the German language, was not widely distributed.

In the following years we had to design the shielding for the electron-positron storage rings DORIS and PETRA. In the previous section we had described our experimental work which had provided us with extensive data concerning the component of electromagnetic cascades. The information for neutron shielding was somewhat slender. We made the best of the situation by evaluating published works and internal papers and the results from our shielding measurements with neutron sources. The data concerning neutron production and neutron shielding were then summarised in a report (Te79). In the same year the well-known book by Bill Swanson was published, the best work concerning shielding at accelerators to date. Later on we extended our work by giving a simple formula for the dose due to high-energy neutrons behind the shielding of electron accelerators (Te88). This work is also nothing more than a critical review of previous works, in this case of two experiments and three theoretical examinations.

In 1979 we received new tasks due to the HERA project. Shielding was not only required for the stored 800 GeV protons but also for the chain of injectors (50 MeV – 7 GeV – 40 GeV). We not only required information concerning the neutron and muon doses above the HERA tunnel (sand shielding) and in the experimental halls (heavy concrete shielding), but also information on the neutron fluence in the tunnel and the dose rate due to activation of accelerator components. Especially the shielding of both the HERA detectors ZEUS and H1 worried us. The experimentalists wanted that their detectors act as self-shielding devices, such as they were used to at our electron storage rings. A shielding wall between detector and staff (as at CERN's SPS) would take up too much room. Furthermore the researchers wanted to remain on top of the detector during operation; however from this position one can at small angles (~10°) see into the tunnel and towards the approaching 800 GeV proton beam. Thus we had the problem of dealing with iron shielding, for which little data was available, together with the problem of shielding at small angles and very high energies.

We again proceeded with a critical compilation of experimental data and theoretical results. This will be shown in an example. For the neutron dose behind a lateral concrete shielding all experimental results at low primary energies have been summarised in a simple formula, which is known as the "Moyer model". Additionally we were able to evaluate the first results from shielding measurements at 200 GeV and 300 GeV carried out at the Fermi National Laboratory. We could use the theoretical results from Keran O'Brien, who had 10 years previously carried out the only analytical shielding calculations for high primary energies. We were especially grateful to receive the Monte-Carlo programs FLUKA from CERN and CASIM from FERMILAB. It was true that these programs were not really able to calculate neutron doses. The cut-off energy, below which the paths of secondary particles are not further calculated, was 50 MeV; neutron doses are also due to neutrons of lower energies. However, the programs did calculate "star densities" (the number of inelastic interactions per unit volume) and deposited energies. From the energy deposited in a layer of water behind the concrete shielding and the assumption of a mean quality factor, one is also able to calculate neutron doses. All these experimental and theoretical results fitted well together and when summarised resulted in a usable method for calculating the neutron dose for high primary energies.

Other required values (neutron fluence in the tunnel or dose rate due to activation) were also assumed to have a linear correlation with the star density. The proportionality constants were taken from various sources, and then the FLUKA or CASIM program was applied to the actual HERA geometry. We calculated muon doses with the MUSTOP program from CERN (it had originally been developed in Berkley) or with the CASIMU program which was an extension of CASIM.

These were the foundations for our environmental report of 1980 in which we presented the protection of the population against radiation from the proposed HERA storage ring. It was the starting point for an extended public relations action in order to waken understanding for the work at DESY and to convince the people that the new facility was harmless. This was an important task since the planned tunnel would run underneath numerous private properties (at a depth of 15-20m) and DESY required the consent of each property owner. Numerous meetings took place with residents, societies and local representatives of political parties at which a representative of the radiation protection group and a member of the DESY directorate took part. An open day, which was subsequently regularly repeated, brought thousands of the Hamburg populace onto the site. These efforts were worthwhile; no opposition of any kind arose from the population to the project. We were also lucky that competent physicists were members of the Hamburg supervisory authorities with whom we were able to solve the problems concerning authorisation in an unbureaucratic manner.

In the following years we designed the additional shielding for the synchrotron tunnel (DESY 3) and for PETRA which were now to be proton injectors. The proposed H1 and ZEUS detectors had to be surrounded with additional 50 cm concrete in the central region in order that they could be considered to be self-shielding. For solving the problem of shielding at small angles (10°–20°) – a rather unusual shielding geometry at high energy accelerators – we used 2 m iron and 1 m heavy concrete to be on the safe side, it was not an easy task for the group who had to install this shielding.

At this point we should mention that the approximative methods of dose calculation (calculation of star densities, use of the Moyer-model) used for dimensioning of shielding can be quite adequate. In almost all cases the uncertainty in the calculation of doses behind shielding is not due to the computational method or to inaccurate material data but rather are due to the necessary assumptions concerning loss of the primary beam at the location under question. Everyone who has been involved with shielding knows the endless discussions of whether for the beam loss the "worst case", the "technically possible case", the "typical case", the "mean case averaged over one year" or some other scenario has to be assumed. Often one can only estimate the order of magnitude of the beam loss, for example during one year, and hence the calculated yearly dose cannot be more exact.

Hence we considered it to be useful to present a summary of the approximative shielding calculations that we have used. From the shielding considerations for a proton linear accelerator we obtained simple formulae for calculating the lateral shielding of proton accelerators in the range 50–1000 MeV (Te85), which are still of use today. We presented the methods used for the high energy region in a longer article (Te86). Here we concentrated our efforts especially on the lateral shielding behind a thick target – the most important shielding geometry – using the FLUKA Monte-Carlo program. We found that for high primary energies the Moyer-model is too simple for describing neutron doses caused by the hadronic cascade (Di89a). However, we had no idea that this work would be out of date within a few years. The times where one calculated neutron doses from "star densities" and "absorbed dose in water" came to an end – more exact calculations became possible.

At the end of the 1980s the mainframe computers became more and more powerful and large amounts of storage capacity were available. More expansive Monte-Carlo calculations could be carried out. It became possible even for high primary energies, to track secondary particles through a shielding down to very low energies and hence finally calculate the dose for tissue-equivalent material. We did not carry out the further developments of the programs ourselves. This would not have been possible with a group with 2 physicists who were also responsible for radiation protection at 10 accelerators. We have already mentioned that we had obtained the important programs from the radiation protection groups at the accelerator centres CERN, FERMILAB and SLAC, with whom we had good connections. Furthermore we were lucky enough to have visiting scientists for two-year periods in our group. In collaboration with them we were able to produce results that were of general interest and not only pertaining to the problems at DESY.

The above-mentioned calculations with the FLUKA and CASIM programs were carried out together with Chiri Yamaguchi from the Japanese laboratory for high-energy physics KEK. He often worked with our group between 1981 and 1987. We also had important use for the Monte-carlo program EGS, a program for simulating electromagnetic cascades, which was developed to perfection at SLAC in Stanford. We were able to use it for the calculation of the dose due to synchrotron radiation per circulating charge within a dipole magnet of the PETRA electron-positron storage ring and also in the entire tunnel cross-section of PETRA. We obtained good quantitative agreement with the above-mentioned dose measurements. Other calculations were carried out in this field in order to better understand the above-mentioned radiation damage. Here again Chiri Yamaguchi helped us. We used the same program for studying the production and shielding of e-γ stray radiation due to high-energy primary electrons. These calculations were carried out between 1986 and 1987 together with Pang Jianqing from the Institute for Plasma Physics at the Academica Sinica in Hefei (China) (Di88, Di89b). The results were so parameterised that one could easily obtain the dose for various target geometries, target materials and shielding materials, and for the complete angular range in the energy range 0.15–50 GeV. We were able to verify the calculations by means of our old measurements from 1977.

The collaboration with Jan Zazula from the Cracow Institute for Nuclear Physics (Poland) were especially successful. As an expert for transport calculations for particles in material, he recognised that the available mainframe computers allow calculations of hadronic cascades with the FLUKA program in which particle fluences can be treated even at very low energies – in the case of neutrons down to thermal energies. He combined FLUKA with parts of the world-wide used MORSE program for the transport of low energy particles, with the EVAP program (the version from the nuclear research facility Jülich, Germany) for calculating the emission of particles from excited nuclei, and with the HILO data library from Oak Ridge (USA). In this way it was finally possible to calculate neutron doses behind a shielding or in an accelerator tunnel or fluences of low-energy neutrons in thick absorbing materials (Za90, Za91, Te91b). We were relieved that these calculations, applied to the HERA problems, confirmed our earlier estimates. The collaboration with the Cracow institute was continued in 1990–92 with Dominik Dworak. With the extended

FLUKA program we were able for the first time to calculate the photon dose behind concrete shielding of proton accelerators (Dw92) as well as the attenuation of neutron and photon doses within the access labyrinths of accelerators (Di93). We again compared the latter calculations with our earlier measurements.

5. The Prospects

This review of the past 30 years shows that in the early days the information required for radiation protection was obtained solely from measurements. Commercial instruments had to be modified for use in the radiation fields of accelerators. Two important problems were their behaviour in pulsed fields as well as (for neutron dosimeters) their sensitivity to neutrons up to energies of 150 MeV. Improved performance of mainframe computers lead to the increasing importance of Monte-Carlo calculations. Nowadays the doses behind shielding, particle fluences within an accelerator tunnel, induced radioactivity or the sensitivity of a neutron dosimeter can be calculated. One has of course to exercise care. Monte-Carlo calculations have the unpleasant property that they always produce a result. The results of calculations for high-energy physics must be proved experimentally. This is even more important for dosimetric calculations. In this case fluences of particles with very low energies are calculated for high primary energies; for neutrons this can mean an energy reduction of 12 orders of magnitude. Inexact cross-sections or unchecked usage of variance reduction techniques can then lead to large errors. We have always attempted to verify our calculations with our earlier measurements as far as this was possible.

This review also shows that our theoretical work was only possible due to successful international collaboration. Dominik Dworak has returned to his home institute. We do have a computer connection to the Cracow institute and also with the CERN radiation protection group. The collaboration continues and we hope for interesting results from further calculations.

At the beginning of this article we reported on a shielding experiment from 1963 and it is a pleasure to finish with another experiment. Manfred Höfert and his colleagues in the radiation protection group at CERN succeeded in having 3 periods (each of one week) of main user time allocated at an external SPS hadron beam. Radiation protection groups from various countries can perform measurements with primary energies of 125 and 200 GeV behind concrete or iron shielding to test their dosimetry systems or quantitatively check their shielding calculations. This is the most generous radiation protection experiment that has ever taken place at an accelerator. We have already obtained very good results from the first measuring period. At the time of writing Herbert Dinter and Brunhilde Racky are again in CERN and we await new results with interest.

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