**ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH**

*Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics*

SAFETY COMMISSION

CERN-SC-2008-002-RP-PP
EDMS : N^o 925026

A (CERN) HISTORY OF ACCELERATOR SHIELDING

by

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Abstract

This paper provides an historical overview of accelerator shielding of accelerator shielding studies at CERN. CERN accelerators and the related shielding problems span 50 years of history and cover all major aspects which can be encountered in accelerator radiation protection. Namely: various accelerated particles (electrons, positrons, protons, antiprotons, heavy ions), a wide range of energies, from a few MeV/u of the present ion injector linac to the 7 TeV of the Large Hadron Collider now coming into operation, several types of primary and secondary beams (including pions, muons and neutrinos), beam intensities, and type of accelerators, from the 600 MeV synchrocyclotron of the mid-fifties to proton and ion linacs, synchrotrons providing extracted beams for fixed-target physics (the PS booster, the PS and the SPS), an electron-positron collider (LEP), proton-proton colliders (the ISR and the LHC) as well as a proton synchrotron converted into a collider (the SPS in the mid-eighties).

CERN, 1211 Geneva 23, Switzerland
27 May 2008

A (CERN) HISTORY OF ACCELERATOR SHIELDING

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Invited talk at the ICRS-11 and RPSD-2008, April 13-18, 2008, Pine Mountain, Georgia, USA

From the early days, accelerator shielding – and radiation protection in general – has been influenced by the increasing knowledge of health effects of ionising radiation, which has progressively decreased the dose rates allowable in occupied areas. At the same time the tools available for estimating shielding have more and more benefited from increasing computing power. Nonetheless, the simplified models of the early days are often still useful for a first estimate before going into complex and detailed Monte Carlo simulations.

This paper will provide a (forcedly brief) historical overview of accelerator shielding. As the subject is extremely vast, it will be restricted to a review of the various phases of accelerator shielding studies at CERN. CERN is a good example as its accelerators and the related shielding problems span 50 years of history and cover all major aspects which can be encountered in accelerator radiation protection. Namely: various accelerated particles (electrons, positrons, protons, antiprotons, heavy ions), a wide range of energies, from a few MeV/u of the present ion injector linac to the 7 TeV of the Large Hadron Collider now coming into operation, several types of primary and secondary beams (including pions, muons and neutrinos), beam intensities, and type of accelerators, from the 600 MeV synchrocyclotron of the mid-fifties to proton and ion linacs, synchrotrons providing extracted beams for fixed-target physics (the PS booster, the PS and the SPS), an electron-positron collider (LEP), proton-proton colliders (the ISR and the LHC) as well as a proton synchrotron converted into a collider (the SPS in the mid-eighties).

I. INTRODUCTION

This conference marks the 50th anniversary of the first Conference on Radiation Shielding and in this context this paper will try to provide a condensed review of the major steps that had occurred in accelerator shielding design over the past half century. The original title of this paper should have been “History of accelerator shielding”, but finally I decided to limit this review to CERN’s shielding history for various reasons. First, the subject is very vast, and collecting all relevant information from the various accelerator laboratories around the world would have required too much time, I

would not have had the time anyhow to address everything in a few pages, and I would have almost certainly forgotten something important. Second, being at CERN since several years has allowed me to have easier access to past and present information and direct experience on recent developments. Last but not least, and in fact most important, CERN is a representative example as its accelerators and the related shielding problems span 50 years of history and cover all major aspects which can be encountered in accelerator radiation protection. CERN’s machines accelerate, or have accelerated in the past, various particles (electrons, positrons, protons, antiprotons, heavy ions) to a wide range of energies, from a few MeV/u of the present ion injector linac to the 7 TeV of the Large Hadron Collider now coming into operation. CERN provides the physics community with several types of primary and secondary beams (including pions, muons and neutrinos) over a broad range of beam intensities. CERN runs or has run various types of accelerators, from the 600 MeV synchrocyclotron of the mid-fifties to proton and ion linacs, synchrotrons providing extracted beams for fixed-target physics (the PS booster, the PS and the SPS), an electron-positron collider (LEP), proton-proton colliders (the ISR and the LHC) as well as a proton synchrotron converted into a collider (the SPS in the mid-eighties). One of them – the Proton Synchrotron (PS) – was switched on in November 1959 and thus it is in operation since practically 50 years. This paper will thus not address shielding of electron and hadron accelerators for medical uses.

From the early days, accelerator shielding – and radiation protection in general – has been influenced by the increasing knowledge of health effects of ionising radiation, which has progressively decreased the dose rates allowable in occupied areas. At the same time the tools available for estimating shielding have more and more benefited from increasing computing power. Nonetheless, the simplified models of the early days are often still useful for a first estimate before going into complex and detailed Monte Carlo simulations. This paper will try to give a more general view of shielding than just going through the various CERN accelerators. It will first briefly illustrate the fundamental steps that have occurred in accelerator shielding approaches, highlighting some specific issues. It will then review the major stages that have marked the shielding design of CERN

machines, and then have a quick glimpse into the future. For some of the historical development I have followed the track provided by ref. [1].

II. THE VARIOUS APPROACHES TO ACCELERATOR SHIELDING

We can – maybe somehow arbitrarily – distinguish three steps in the evolutions of techniques for shielding assessment:

1. Early shielding designs based on cosmic ray data and extrapolations (or guesses)
2. Point-source line-of-sight models, in particular the Moyer model for energies above a few GeV
3. Monte Carlo radiation transport codes

These periods have not always been in phase at electron and proton accelerators and only relatively recently the same techniques have started to be applied at both.

In a number of practical cases and over a broad range of shield thicknesses, a simple point kernel equation is sufficiently accurate to estimate shielding (see, for example, refs. [2, 3]):

$$H(d,\theta) = r^{-2} H_0 \exp[-d(\theta)/\lambda] \quad (1)$$

where $H(d,\theta)$ is the dose equivalent at depth d and angle θ in the shield, H_0 is the source term at unit distance from the source (that is, the dose equivalent extrapolated to zero depth in the shield), r is the distance from the source to the point of interest outside the shield and λ is the attenuation length for dose equivalent through the shield. The Moyer model [4] uses a point kernel equation for calculating secondary radiation shielding for proton accelerators with energy above 3 GeV. It was first developed for the shielding of the 6 GeV Bevatron and later improved following the shielding studies for the next high-energy accelerators and new experimental data from dedicated shielding experiments like the one performed at CERN and discussed below. A version of the model also exists for a linear radiation source [5].

A hybrid approach between the second and the third ones above is the determination by Monte Carlo simulations of source terms and attenuation length as a function of energy and emission angle, to be applied in generic shielding situations with simple models. At intermediate energies the attenuation properties of a material vary rapidly with energy, so that the two parameters have to be calculated as a function of energy (see, for examples, refs. [6, 7] which include an extensive comparison with other available literature data). It is worth recalling that the “source term” which appears in expression (1) (as well as in the Moyer model) does not refer to a bare source but to a virtual source derived from extrapolating the dose equivalent deep in the shield to

zero thickness. Therefore it must not be used for e.g. estimating the dose rate from an unshielded source, or as a source term for evaluating transmission of radiation through a duct or a maze. It is also worth recalling that the simplified expression (1) does not show the build-up term present at shallow depths in the shield [2, 6, 8].

Point-source line-of-sight models can be directly applied to shielding proton accelerators of energy up to about 400 MeV, where the radiation source generated by the interacting protons is limited to a distance equal to the proton range. At higher energies the cascade does not generally develop in the target and many of the high-energy secondaries can escape and generate a cascade in the shielding. In addition the cascade extends on a comparatively long distance as compared to the dimension of an accelerator tunnel, and thus can no longer be regarded as a point source. In such cases the wall-source model described in ref. [8] may be more appropriate.

Still today, with state-of-the-art Monte Carlo radiation transport codes and extensive computing power available, it is often useful – although not always possible – to perform a first assessment of the required shielding thickness by using a simplified approach, to be verified at a more advanced stage of the project with a Monte Carlo simulation in a more realistic geometry of the facility. Often this simplified approach provides a conservative estimate of the required shielding.

Accelerator shielding is not limited to calculation of barriers, but also includes assessment of skyshine (and of roof shielding), as well as design of ducts and mazes (which can be very large, like the access shafts of LEP and LHC, some of which are around 20 m in diameter and more than 100 m in depth) penetrating the barriers. Apart from Monte Carlo simulations, the assessment of neutron streaming through ducts and labyrinths can often be performed to a sufficient level of accuracy with universal transmission curves, so called as the depth in the duct or leg is normalised to its cross-sectional area [2, 9].

Here we just show two examples. Figure 1 shows the attenuation of neutron radiation in the LEP PM18 shaft (80 m deep and 14 m in diameter) determined experimentally at three LEP energies (94.5, 100 and 103 GeV), compared with the transmission curves for a neutron plane source and a neutron line source [10]. Figure 2 compares instead the predictions of the model with detailed Monte Carlo simulations with the FLUKA code [11, 12] performed for the waveguide and ventilation ducts of the new CERN 160 MeV injector linac [13] (see below).

Fig. 1. Attenuation of neutron radiation in the access pit PM18 (14 m in diameter and 80 m in depth) measured at three LEP energies (94.5, 100 and 103 GeV per beam); d is the distance from the bottom end of the pit and A is the cross sectional area of the pit. The uncertainty on the measurements is $\pm 30\%$. The attenuation for a neutron plane source and a neutron line source is shown for comparison [10].

Fig. 2. Transmission of neutrons through a 3-leg duct: comparison of Monte Carlo simulations with the FLUKA code and analytical estimates made with the universal transmission curves. Dots: FLUKA, line: model. The dotted lines for the second and third leg indicate the confidence limits [13].

III. SHIELDING CERN'S ACCELERATORS

III.A. The Proton Synchrotron (PS)

The convention to set-up a “Conseil Européen pour la Recherche Nucléaire”, which later became known as CERN, was signed by eleven European countries in 1952. It then took two more years before the laboratory was officially funded in 1954. The laboratory had the mandate to build a 28 GeV proton synchrotron (PS), the largest accelerator of the time, a very challenging project, and at the same time to build and make operational a more “conventional” 600 MeV synchrocyclotron on a shortest time-scale. The synchrocyclotron started operation in 1957, followed after two years by the PS (Figure 3).

Fig. 3. Aerial view of the Meyrin site in winter 1963. The PS tunnel is clearly visible (photo CERN)

At that time there was neither experience nor knowledge about high-energy accelerators, and the PS shielding was designed on the basis of estimations made from cosmic ray data [14]⁽¹⁾. Being the first machine of

⁽¹⁾ As we will see below, the next injector linac to be built at CERN and for which the civil engineering work will start in fall 2008, will be installed at the place of a small hill conventionally known as the “Mont Citron”. There has recently been long discussions about the origin and the purpose of the Mont Citron, with even speculations that it was originally designed to shield the CERN fence from stray radiation from the PS. Finally it turned out that it is most likely just soil from excavation work sheltering an old water tank. But at least the origin of the name now seems to be understood!

such energy, with an exploitation program which included extracted beams and expected future upgrades, the radiological problems were taken seriously by the CERN management and in the early sixties CERN was one of the first laboratories (maybe the first) to create a strong health physics group. It is interesting to note that a panel of experts convened to advise the management made the observation that *“errors in estimating shielding requirements would be more costly than the scientific efforts necessary to produce better estimates”* (ibid ref. [1], page 172), thus pointing to the need that the group should not just perform routine radiation protection tasks but be involved in scientific activities (which also included instrumentation and dosimetry). The above statement is still more than valid.

The new high-energy accelerator available thus boosted a shielding experiment with 10 and 19 GeV protons in 1962, which involved six institutes: ABS (Hannover), DESY (Hamburg), ORNL (Oak Ridge), Rutherford Laboratory (Chilton), SLAC (Stanford) and CERN [15]. A second shielding experiment at the PS took place in 1966 in collaboration between CERN, the University of California Radiation Laboratory at Berkeley and Rutherford lab, the results of which were summarised in a 360-page report [16]. Activation detectors, proportional counters, emulsions, thermoluminescent dosimeters and an air ionization chamber were used to study the composition, intensity, and energy spectrum of the radiation field, and the attenuation in the earth shield. Target angular-distribution studies were also undertaken with activation detectors, as were studies of tunnel transmission, and concrete and steel activation (Figure 4). The purpose of the experiment was *“to carry out an extensive study of many of the major uncertainties in the radiation environment of the 28-GeV CERN proton synchrotron (CPS). Proton beam loss, neutron spectra, radiation levels in the accelerator room, and transmission of radiation through earth shielding and along tunnels were measured at 14.6 and 26.4 GeV/c...The data obtained have been qualitatively explained by Monte Carlo calculations.... The transmission of radiation through the earth shield was analyzed ... through generalization of an empirical model.... Excellent agreement is obtained with the experimental data. The conclusion was that “the success of the model in explaining the observed radiation field at the CPS gives confidence in extrapolation to accelerators in the energy region around 200 GeV. The transmission of radiation along tunnels was studied and successfully interpreted in terms of a simple model.”*

A third milestone in international collaboration and further progress with accelerator shielding issues occurred with a conference held at CERN in 1971 on protection against accelerator and space radiation [17]. In fact there are similarities in the stray radiation field encountered around high-energy accelerators and that found at

commercial flight altitudes and in space. In turn there are similarities in the problems related to shielding stray radiation from high-energy accelerators and in the protection of humans from radiation in space missions (see, for example, ref. [18]). The cosmic radiation field can partly be simulated at high-energy accelerators [19].

Fig. 4. The 1966 PS shielding experiment: vertical cross section of the PS accelerator tunnel surmounted by the earth shielding pierced by the vertical holes where dosimeters were placed. Additional dosimeters were placed in the buckets suspended from the tunnel roof (from ref. [16]).

The PS was later submitted to major improvements in order to increase the beam intensity. This included the commissioning in 1968 of a 4-ring 800 MeV booster synchrotron (the energy of which was later raised to 1.4 GeV). At this stage it was realised that at intermediate energies the attenuation properties of a material, expressed by the attenuation length, varies rapidly with energy (see above).

Despite the overall increase of the beam circulating in the PS by at least a factor of 100 from its early days to the present, the PS shielding is still adequate. Only recently, with the further increase of the beam intensity for CNGS and LHC operation, it appears that at specific locations the available shielding is reaching the limit and some countermeasures are being implemented. These are essentially focussing on reducing or displacing the beam losses rather than reinforcing the shielding itself [20]. This solution proved very effective as in the most critical location the dose equivalent rate due to stray radiation reduced from 2006 to 2007 by as much as a factor of 80.

III.B. Skyshine and roof shielding

Early measurements around the synchro-cyclotron revealed a clear increase in neutron level with distance from the accelerator. The importance of skyshine and the necessity for adequate roof shielding was a problem not always timely realised in various laboratories. The CERN antiproton accumulator completed in 1980 (AA, lately

converted into the antiproton decelerator, AD) was also originally designed without roof shielding. At the LNF laboratories of INFN in Frascati, Italy, the insufficient overhead shielding of the electron synchrotron was understood only after neutron measurements with a newly designed instrument could be performed. Only later a proper roof shield was put in place over ADONE [1]. The same occurred with the 6 GeV Bevatron of the Lawrence Berkeley National Laboratory, which operated without roof shielding from 1954 to 1962, other than the about the 1 m of steel provided by the magnet yoke and pole tips and some local concrete shield placed over sources of radiation in machine regions where there were no magnets [21]. The same problem has been recently spotted again at CERN in one of the experimental SPS areas: FLUKA calculations have shown the influence of the thin (3-5 mm thick) roof shielding of the building. The experiment itself is shielded “only” by thick concrete walls on the sides and some of the dose to personnel in the counting rooms is actually coming from backscattered radiation from the roof.

III.C. The Intersecting Storage Rings (ISR)

There are typically two situations which have to be considered when designing a shield. The first is routine accelerator operation, for which one can expect (more or less) constant losses at (more or less) well defined locations in the machine (such as septa, collimators, dumps, aperture restrictions). The second is that of a full loss of the beam at a defined location or over a given section of the accelerator. In the former case one has to design the shield so as to meet the requirements of ambient dose equivalent rate according to the classification of the area past the shield. In the latter case one has to assess the dose rate dH/dt in the accessible area as generated by the beam loss, define the maximum acceptable integrated dose H_{max} that can be received by the personnel who may be present in the area, and then make sure that the accidental condition cannot last for a time T longer than $T = H_{max} / dH/dt$. This in turns means to specify that the accelerator control system must be capable of stopping the beam within the time T . If the loss is “catastrophic”, that is if it cannot continue over a certain time, but it occurs in a single shot at a defined point and will cause such a damage to the accelerator (a quench in a superconducting magnet, a large vacuum leak, a physical damage to a component vital to the machine operation) so that the beam is automatically stopped, then one has to evaluate the integral dose generated by such event as a function of shielding thickness, and dimension the barrier accordingly. The final shielding thickness is the largest value imposed by the two conditions, routine and accidental. It is often found that the former dictates the shielding design.

The project for the Intersecting Storage Rings (ISR), the world’s first hadron collider, was approved by the CERN council in 1965. The machine was designed and built in a few years and started operation in 1971 (Figure 5). Due to the very high current (several tens of amperes!) of the two 31 GeV counter-rotating proton beams, the ISR were conceived as “lossless” machines, so that for the first time in CERN’s history the shielding had to be designed essentially to cope with the case of catastrophic beam loss rather than a routine low-loss condition.

Fig. 5. The Intersecting Storage Rings (ISR), the world’s first hadron collider (photo CERN)

Although it has little to do with shielding, it is worth mentioning that the stochastic cooling was invented by Simon van der Meer at that time and tested in the ISR. Finally it turned out not to be necessary for ISR operation, but it was ideal in a machine of lower beam current. Stochastic cooling was successfully implemented in the early eighties when the SPS was converted into a proton-antiproton collider for the UA1 and UA2 experiments that ultimately led to the Nobel Prize for Van der Meer and Carlo Rubbia. Stochastic cooling was mainly applied in the antiproton accumulator, where stacking and cooling was the mechanism whereby the antiproton currents were accumulated.

III.D. The Super Proton Synchrotron (SPS)

A few years after the proton synchrotron started operation the physicists were already dreaming of an

accelerator of energy ten times higher, a “super proton synchrotron”. Two projects were launched, one at CERN for a 300 GeV accelerator and the other at Berkeley for a 200 GeV machine. The CERN project later became the SPS with energy of 450 GeV. Shielding optimisation and activation of soil and groundwater were major issues in the project. The 1966 shielding experiment mentioned above was set-up to provide a solid base for extrapolation to the higher energies of the future accelerators. In 1968/69 a European study team for the 300 GeV project was created and organised in working groups, one of which to address specifically the radiation problems. The results were published in a comprehensive report [22]. A chapter was dedicated to the joint treatment of hadronic and electromagnetic cascades, another chapter was devoted to shielding against muons, and another one to the transmission along ducts and to skyshine.

The SPS was the first CERN accelerator for which the shielding calculations were performed via Monte Carlo simulations, using the original version of the FLUKA code [23]. The labyrinths were also designed via Monte Carlo calculations using SAMCE [24]. It was also with the SPS that muon shielding for the first time became a real issue.

A first hint of a muon problem tangential to a target is found in one of the very first survey reports of the PS, but that was probably not realized at that time [1]. Only with the SPS muon shielding was fully understood as a real problem to be tackled. To avoid muon problems from the accelerator itself, the SPS was installed approximately 40 m underground. The extracted proton beams were taken to target stations (for the production of secondary beams) located about 15 m below ground level, so that muons from the target areas also remained confined underground. Nonetheless, some of the muons from the targets could still reach the experimental areas and muons generated from secondary pions transported in the beam lines to the experiments also added their contribution. For operation with high intensity pion beams, the areas downstream of the experimental halls had to be fenced off. Whereas in the PS, beam stoppers were used in the secondary beam lines, with the SPS this was not possible: they would have been very long to absorb the hadronic cascade and they would have been anyhow useless against the muons (see Table 1). In the SPS experimental areas the data acquisition rooms were placed all around the hall but at an upper level with respect to the beam lines, in order to avoid the muon cone (in the past, they would have been located at beam level). Again recently muons from the SPS had to be considered in estimating the radiation levels in the injection sectors of the LHC ring expected during injection tests of the 450 GeV beams [27].

The conversion in the early eighties of the SPS into a proton-antiproton collider and the construction of two new large underground experimental areas close to the

ring implied, apart for modifications to the SPS itself, the commissioning of an antiproton source (the AA). For radiation protection the challenges were the construction work of the experimental areas during SPS operation and later adapting the shielding conditions to alternating high and low intensity operation.

TABLE 1. Comparison of the longitudinal thickness in metres of iron shielding required to achieve $10 \mu\text{Sv h}^{-1}$ due to the hadron and muon components of the cascade for a proton beam intensity of 10^{12} s^{-1} . (Hadron data are from ref. [25], muon data were calculated by G.R. Stevenson using the MUSTOP programme [26].)

Proton Energy	Hadron shield	Muon shield
5 GeV		3.4
10 GeV	4.6	6.0
30 GeV		14.0
100 GeV	8.4	36.0
300 GeV		77.0
1 TeV	10.2	170.0

At about the same time the decision was taken to build the Large Electron Positron collider (LEP) – the largest accelerator ever built – and use the SPS as its injector. Since the SPS was not designed for lepton operation, the concern was that synchrotron radiation could cause radiation damage to the machine. A system of lead shield and tungsten collimators was built to prevent it. Finally the SPS never experienced any problem because of electron/positron operation.

In 1986 the SPS went again through another upgrade program to accelerate heavy ions up to 158 GeV per nucleon ^{208}Pb . The major problem occurred with beams of deuterons. Whereas with protons the experimental areas could only receive secondary beams with intensity much lower than the SPS beam, the primary deuteron beam of non-negligible intensity could instead be channelled to the experimental area. The same problem later showed up with ions with the same Z/A , such as ^{12}C and ^{16}O .

With lead ion beams, despite their much lower intensity as compared to the proton beams, one has to consider that the production of secondary particles is roughly proportional to the projectile mass number. Even low intensity beams could cause significant radiation levels, in particular in the experimental areas where beam lines were not shielded but only fenced off. More recent measurements have shown that the spectral fluence of the secondary neutrons outside a thick shield is similar for light (protons) and heavy (lead) ions of comparable energy per nucleon stopped in a thick target. The approach of considering a high-energy lead ion as an independent grouping of free protons turned out to be

sufficiently accurate for the purpose of evaluating the ambient dose equivalent of secondary neutrons outside thick shielding. At the time (only a few years ago) in which Monte Carlo codes were not yet capable of reliably transporting heavy ions, it was shown that the neutron yield for lead ions could be estimated from the results of a Monte Carlo simulation for a proton beam of the same energy per nucleon [28-30].

III.E. The Large Electron Positron collider (LEP)

The LEP project was approved in 1981. Although it was the largest accelerator ever built and it required the excavation of a new underground tunnel 27 km in circumference at a depth varying between 50 and 140 m, the project took only eight years to complete. The first beam circulated in the collider on 14 July 1989. LEP operated at 45 GeV per beam until 1996, after which the energy was progressively increased up to 105 GeV in 2000, the final year of operation. The secondary radiation mainly consisted of electromagnetic radiation and neutrons of energy up to several MeV. In addition, the circulating beams produced a very intense synchrotron radiation (SR) – which rose dramatically with beam energy – the spectrum of which exceeded the threshold for photoneutron production at 100 GeV.

LEP was the first electron accelerator at CERN, and CERN had no previous experience with electron accelerator shielding. In spite of the fact that the accelerator was deep underground, some shielding problems near the experiments and in the klystron galleries which were running parallel to the main tunnel had to be addressed. The main radiation issue was indeed SR and its streaming through penetrations. In addition, shielding was required around the vacuum chamber to minimize radiation damage. The MORSE Monte Carlo code [31] was mainly used for the LEP shielding calculations. No program was available to handle photonuclear reactions, so that neutron production and activation calculations were done by empirical methods or using Swanson's book [32]. The ducts for the RF waveguides connecting the LEP tunnel with the klystron galleries were studied via mixed calculations using EGS (for the photon source), published HETC data (neutron source) and MORSE (neutron and photon transport) [33]. The environmental impact of the new accelerator was addressed before construction began [34]. The predictions of the radiation level in the LEP arcs due to scattered SR was later confirmed by measurements carried out over the years at each LEP energy upgrade [35].

A special problem in LEP was posed by the conditioning of the superconducting RF cavities in the tunnel during machine shutdown. These tests required preventing access to the given section of the tunnel, as stray electrons accelerated in the cavities and striking their structure produced a very intense X-ray radiation

with energy extending to several MeV [36]. Adequate protection to allow access to the adjacent arc during shutdown periods was provided by the mazes installed in 1996 for shielding synchrotron radiation during LEP operation. These mazes were built in the machine tunnel between the straight sections and the arcs, before the run at 86 GeV in 1996. The main aim of these so-called “RF chicanes” was to reduce streaming of the SR into the RF sections. The installation of these chicanes actually put in evidence a source of radiation independent of SR, and of comparable intensity, linked to the operation of the superconducting RF cavities, as shown in Figure 6 [10].

Fig. 6. Attenuation of radiation by the RF chicane in LEP measured at six beam energies (80.5 to 102 GeV). The chicane separated the straight section (SS) housing the superconducting RF cavities (left) from the arc (right). The chicane was built to prevent synchrotron radiation streaming from the arc into the SS. The figure shows that an even stronger radiation source, produced by the operation of the cavities, was actually present in the SS. Dose rates are normalised to 1 Ah of total circulating beam current (Gy per Ah) [10].

III.F. The Large Hadron collider (LHC)

When the Large Hadron Collider project was approved for installation in the existing LEP tunnel, the radiological problem to tackle was that a hadron machine produces much more radiation than an electron machine. Just to quote one example, the LEP experiments were a negligible source of secondary radiation, while proton-proton collisions in the LHC are a major radiation source. The LEP experimental halls were accessible during beam on (with radiation levels below the natural background on the surface) [10, 37], while with the LHC this will not at all be possible.

Concerning shielding, the main constraint for the installation of the LHC in the existing LEP tunnel was not

related to the tunnel itself, which was sufficiently underground to shield direct stray radiation and contain the muons in the soil, but rather to the various access shafts distributed around the ring. In order to minimize LEP construction costs, the shafts were positioned as close as possible to the ring, so that substantial shielding had to be added in view of LHC.

The first round of radiation studies was completed in 1984. Shielding, induced radioactivity and radiation damage to machine and detector components were equally important issues with the LHC [38]. The upgrade of the FLUKA Monte Carlo code to its present version was started in 1988 at the national Institute of Nuclear Physics (INFN) in Milano (Italy), to improve – among other things – electromagnetic transport, physics of particle interaction at multi-TeV energies and low-energy neutron transport. FLUKA [11, 12] has now become “The Universal Tool” for radiation calculations at CERN.

III.G. CERN Neutrinos to Gran Sasso (CNGS)

The CNGS (CERN Neutrinos to Gran Sasso) facility has been designed to generate at CERN an intense artificial muon–neutrino beam aimed at the Gran Sasso Laboratory in Italy. The commissioning of CNGS in 2006 has required increased beam intensities in the PS and SPS, which has implied some countermeasures to be taken. For example, shielding had to be reinforced in the sextant of the SPS where the new extraction elements (in fact common to CNGS and LHC) were installed. However, most of the shielding design effort went into the CNGS target area. The target consists of 13 graphite rods. Positive pions and kaons produced in the target from proton collisions are focused into a parallel beam by a system of two pulsed magnetic lenses, called horn and reflector. Due to very high proton beam intensity, this region is a very intense source of secondary radiation and had to be heavily shielded in order to reduce the personnel exposure due to induced radioactivity during shutdown [39]. A service tunnel has been built parallel to the tunnel housing transfer line and target area, in order to avoid unnecessary personnel exposure.

In fact, shielding is not only meant to protect personnel but also instrumentation. This was readily realised during the first CNGS run, where some electronics located in front of the opening of the passages connecting the CNGS target area with the parallel service gallery suffered radiation damage. Countermeasures had to be taken in order to avoid similar failures in the future.

IV. CERN’S FUTURE ACCELERATORS

To ensure a long lifetime to the LHC, in the coming years CERN will put a substantial effort into the renovation of its injectors. The PS complex, made up of proton and ion linacs, a low energy ion ring (LEIR), the

Booster and the PS, is aged. As stated above, the PS itself will turn 50 next year. A new 160 MeV H^- linear accelerator (named Linac4) has been designed to replace the present 50 MeV proton linac. Civil engineering will start in fall 2008 and the new machine is planned to start operation in 2012. The shielding design has just been completed [40, 41]. The next step will be to replace the booster with a 3.5 GeV superconducting proton linac, for which only a preliminary shielding design has been performed so far [42, 43]. Finally, the PS should be replaced by the so-called PS2, a 50 GeV proton synchrotron to be installed in a new tunnel underground, the conceptual design of which has just started.

V. THE ULTIMATE CHALLENGE IN ACCELERATOR SHIELDING

The ultimate challenge in accelerator shielding could possibly be that of shielding neutrino radiation (or better, its secondaries produced in the material traversed by the neutrinos) from a future multi-TeV muon-muon collider.

Dose equivalent rates due to solar and atmospheric neutrinos and to neutrinos from present day accelerators, including CNGS and similar long-baseline experiments, are insignificant. However, the neutrino flux generated in a muon collider would be much higher. In fact, the radiological hazard would be much larger (up to three orders of magnitude at TeV energies) if the neutrino beam is shielded than if it is left unshielded, because of the secondary radiation (mainly hadrons, electrons and muons) produced in the shielding material (in practice, earth, if the collider is installed underground). The secondaries with the longest range are the muons. The maximum energy of these secondary muons cannot exceed the energy of the collider. The collider must be shielded and the shield must be thick enough to absorb the full muon beam circulating in the ring in case of a beam loss. It follows that the shield must be thicker than the maximum range of all secondaries, i.e. the neutrino radiation emerging from the shield will be in equilibrium with its secondary radiation. For example, for a collider with centre-of-mass energy of 4 TeV installed at a sufficient depth (about 100 m) to guarantee a minimum distance of 30 to 40 km from the surface exit points of the neutrino-induced radiation, the annual dose would be about 2 mSv (Figure 7) [44]. It will certainly not be easy to explain members of the public living at such a distance from the laboratory that they could be exposed to such a radiation dose!

VI. INTERNATIONAL COLLABORATIONS AND EXPERTS’ MEETINGS

Over these past 50 years, the understanding of shielding issues has progressed through a fruitful exchange of information and scientists moving across the

various laboratories, joint committees and international meetings. Apart from the shielding conferences, it is worth recalling here the SATIF series of experts' meetings which started in Arlington in 1994 in conjunction with the Eight International Shielding conference, the SARE meetings which later became the AccApp series of conference, and the Erice courses on radiological protection. Finally, the important role played by NEA and RSICC in distributing computer codes and organisation of specialised conferences should also not be underestimated.

Fig. 7. Dose equivalent due to neutrino radiation at 36 km distance from a muon-muon collider installed at a depth of 100 m (assuming the local earth curvature as perfectly spherical). The contributions from radiation generated by muon decays in the arcs and in the straight sections are shown [44].

VII. CONCLUSIONS

Over the years CERN has benefited from many fruitful exchanges of information and personnel with several accelerator laboratories around the world. In the early days the CERN-LBL-RHEL shielding experiment at the CERN PS [16] provided experimental data which confirmed the similarity of the cosmic ray and of accelerator radiation field. Later radiation study groups were formed for other major projects like the SPS, LEP and the LHC, which included experts from other accelerator laboratories around the world. In particular, there is a long history of collaboration between CERN and SLAC in this domain, with several physicists who started their carrier in one laboratory and ended up the other side of the Atlantic Ocean (and of the US continent).

Over its history CERN has had the opportunity to concentrate in one group the expertise in dosimetry, instrumentation and measurement techniques, the development and application of simulation methods, and the possibility to perform dedicated shielding experiments

along with the accumulation of extensive and systematic routine measurements around its many accelerators.

Finally, it should be underlined that shielding is only one of the issues relevant in accelerator radiation protection. A growing importance has assumed in recent years the calculation of induced radioactivity in accelerator structures (and in the shielding itself) for maintenance intervention, waste disposal and final accelerator decommissioning. CERN has in the recent past had quite an experience with the decommissioning of LEP, which has meant dismantling, partly recuperating but mostly scraping, more than 30,000 tons of material [45]. The LHC now coming into operation has required extensive calculations to predict the amount of induced radioactivity to be expected in the accelerator and in the experiments (see, for example, refs. [46-49]). Environmental aspects have also assumed growing importance over the years, and issues such as activation of earth and groundwater, tritium production, activation of air and fluids in the facility and their environmental impact have to be carefully addressed.

ACKNOWLEDGEMENTS

I am indebted to Alberto Fassò (formerly at CERN and now at SLAC) for the useful discussions which have helped me to shape this paper. I would like to thank my colleagues in the Radiation Protection group Doris Forkel-Wirth, Thomas Otto, Stefan Roesler, Heinz Vincke and Helmut Vincke, for providing me with useful information. I would also like to thank Hiroshi Nakashima (JAERI, Japan) and the conference organisers for giving me the opportunity to prepare this review.

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