The CERN High Energy Accelerator Mixed Field (CHARM) Facility in the CERN PS East Experimental Area

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Abstract

The CERN High Energy Accelerator Mixed Field (CHARM) Facility is currently being constructed in the CERN PS (Proton Synchrotron) East Experimental Area to study radiation effects on electronic components. The chosen location has become available due to the decommissioning and subsequent dismantling of the DIRAC experiment and the CHARM Facility will share it with a proton irradiation facility that is situated further upstream.

The CHARM Facility will receive a primary proton beam from the CERN PS at a beam momentum of 24 GeV/c and a maximum average beam intensity of 6.7E10 protons/second with a maximum pulse intensity of 5E11 protons/pulse and a respective pulse length of 350 ms. The beam will impinge on one out of a set of dedicated targets to produce the desired radiation fields at several experimental positions. These radiation fields can be adjusted by insertion of up to four moveable shielding walls, two made out of concrete and two made out iron. The main purpose of the CHARM Facility will be the investigation of the effects of these radiation fields on electronic components in the framework of the Radiation to Electronics (R2E) project.

First, the radiation field requirements on the CHARM facility by the R2E project are discussed. Then, the radiological assessment of the facility is presented, including the shielding design for the prompt radiation and the optimisation of the residual radiation. Furthermore, the air activation calculations, the resulting radiological impact from the release of radionuclides to the environment and the derived requirements for the dynamic confinement of the air inside the CHARM facility are illustrated.

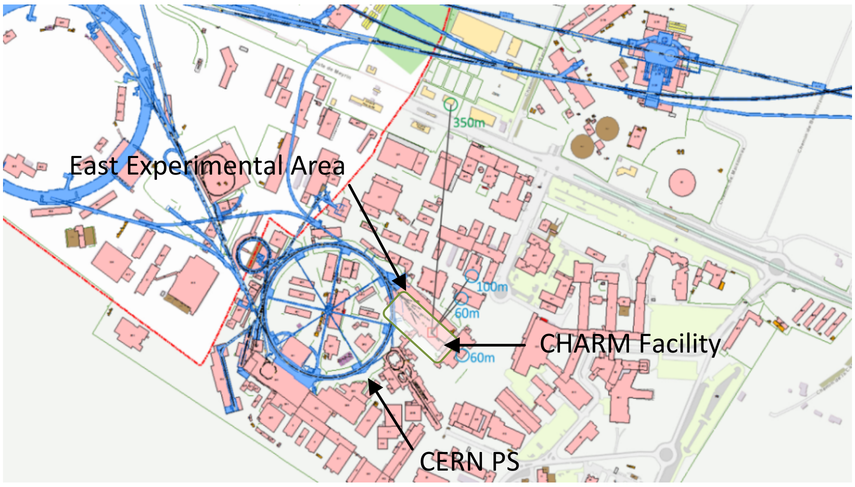
The shielding of the CHARM facility will also include the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target. This facility will allow deep-penetration benchmark studies of various shielding materials. The current plans for the construction and the commissioning of the CSBF are outlined.

Introduction

The CERN High Energy Accelerator Mixed Field (CHARM) Facility [1] is currently being constructed in the CERN Proton Synchrotron (PS) East Experimental Area. The purpose of the CHARM Facility is to provide test locations for electronic equipment with well understood, mixed radiation fields that are typical of the CERN accelerators and other applications of interest. This facility will complement the existing irradiation facilities at CERN such as CERF and IRRAD.

The location of the CHARM Facility on the CERN site and its connection to the CERN PS are shown in Figure 1.

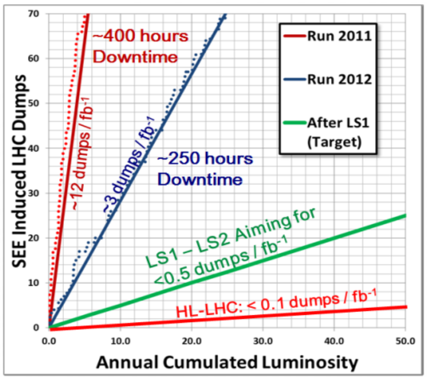
Figure 1. Location of the CHARM Facility connected to the CERN PS



The CHARM Facility will provide test locations for electronic equipment with well understood, mixed radiation fields to the CERN Radiation2 Electronics (R2E) project [2][3][4]. The R2E project was initiated by the observation of significant downtime of the CERN Large Hadron Collider (LHC) due to Single Event Effects (SEE) in electronic devices in the LHC tunnel that triggered the dumping of the LHC beams. This fact is illustrated in Figure 2.

To be able to reach the goal of the R2E project of 0.5 SEE induced beam dumps/fb-1 after the start-up ending the Long Shut-down 1 (LS1) in 2015, extensive testing of electronic equipment that is installed in the LHC tunnel is necessary. The CHARM Facility will provide this testing capability even for tests of entire electronic systems up to dimensions of 1m x 1m x 2m.

Figure 2. LHC beam dumps induced by Single Event Effects (SEE) in electronic devices



This facility is not only useful for testing devices within accelerator representative environments, but its available radiation fields will also be characteristic of ground and atmospheric environments (neutron energy spectra) as well as the space environment (representative for the inner proton radiation belt). In addition, the size of the available test area is such that also larger objects, and ultimately even objects requiring special services (power, cooling, etc.) to be connected for operation, can be irradiated.

Table 1. Annual High Energy Hadron (HEH) fluences for different radiation environments

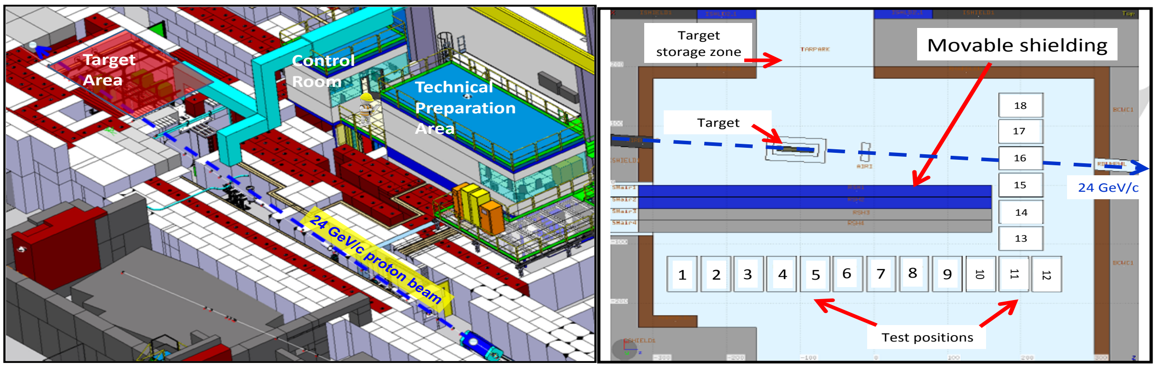
Spectrum	HEH fluxes (>20MeV/cm2/year)
Ground level	$1\text{-}2\times10^5$
Avionic	2×10^7
ISS orbit	1×10^9
LHC machine	1×10^6 - 1×10^{11}
LHC detectors	> 10^{11}

The irradiation chamber is large enough to host a complete accelerator control system (e. g. power converters) but can also host full satellites, and part of cars or planes. For SEEs caused by High Energy Hadrons (HEH) present in the various radiation environments, Table 1 provides a generalised overview of annual fluences, later to be put in the context of what can be achieved in terms of test-time acceleration factor at CHARM. In this respect, so far only few mixed field test areas exist, which often do not provide sufficient beam-intensity or flexible test conditions (e.g two CERN test areas, CNRAD and H4IRRAD, but have significant limitations in beam availability, intensity and flexibility).

Layout and operational parameters

As indicated in Figure 1, the CHARM Facility will be located in one of the experimental halls at CERN. Its surrounding layout is composed of iron and concrete blocks in order to reduce maximum radiation outside the shielding structure. A three-dimensional view of the facility and a horizontal cut of the inner target chamber are shown in Figure 3 (a) and (b), respectively. As shown in Figure 3 (a), the target chamber is large enough to host bulky and complete systems (e.g. satellites) as around 70 m³ of space will be available for radiation tests.

Figure 3: (a) Three-dimensional view of the facility and (b) FLUKA geometry for the target area



Racks 1 to 18 are the regions representing the test locations. The blue, grey and brown plates are iron, concrete and marbles blocks.

Within the facility, a 24 GeV/c proton beam extracted from the Proton Synchrotron (PS) accelerator impacts on a cylindrical copper or aluminum target and the created secondary radiation field is used to test electronic equipment installed at predefined test positions. Copper and aluminum as material choices for the primary beam target are good compromises not only because of their mechanical and thermal properties, but together with the mobile shielding configuration they also allow the creation of a secondary particle spectra representative for the source term of those present in the atmospheric, space and accelerators environments.

To model and choose between the various representative spectra, different shielding configurations are thus available in the facility. Four movable layers of an individual thickness of 20 cm made of concrete and iron can be placed between the target and the test locations in different combinations, thus allowing to modulate the test spectra and adopt them as closely as possible to the radiation field (energy and intensity) aimed for during the tests. The shielding plates are motorised with remote control. The intensity of the radiation field can be modulated by varying the primary beam intensity, the choice of target head, e.g. two massive ones (Al or Cu – the yield of the massive Al target is about 2.5 times smaller than for the massive Cu target) or one with reduced effective density (Al target with holes – it gives an additional reduction by a factor 4), allowing for an overall reduction factor (including beam intensity reduction) of the primary radiation field of 10-100, in total.

In summary, the CHARM Facility will receive a pulsed proton beam from the CERN PS with a beam momentum of 24 GeV/c. There will be 5e11 protons per pulse with a pulse length of 350ms. Under nominal conditions, 2 spills per 45.6 seconds, i.e. per PS super-cycle, will be sent to the CHARM Facility. This is the foreseen operation mode of the facility for the next years. Theoretically, up to 6 spills per 45.6 seconds will be possible in case the East Experimental Area is the only user of the test beam cycles of the PS. Table 2 shows the operational parameters accounting for the number of days of operation per year and machine availability.

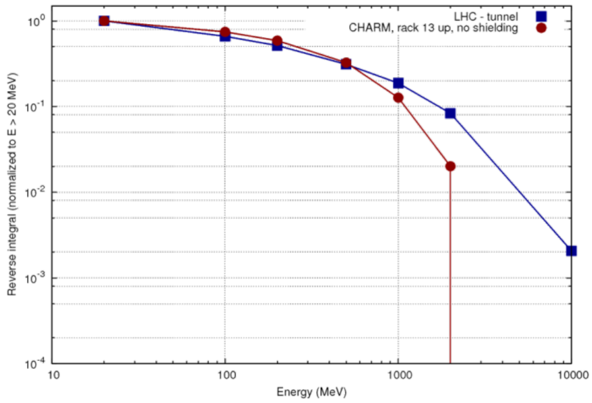
Table 2. Operational parameters of the CHARM Facility

Scenarios	Average proton beam intensity on target	Annual number of protons on target
Nominal (2spills/45.6s)	2.2E10 p/s	3.3E17 p/y
Maximum (6spills/45.6s)	6.7E10 p/s	1e18 p/y

A sketch of the CHARM Facility is presented in Figure 4. Figure 5 shows the comparison of a representative radiation spectrum in the LHC tunnel and the selected location in the CHARM Facility.

Figure 4. Layout of the CHARM Facility

Figure 5. Reverse integral (defined as the integral starting from a given energy up to infinite energy) of the high-energy hadron fluence normalised to the total high-energy hadron fluence above 20 MeV (left) for the LHC tunnel and location 13 in the CHARM Facility



Radiation protection assessment approach

The radiation protection assessment of the facility has been divided into 3 categories that are discussed in the following sections, namely the shielding design for the prompt radiation, the optimisation of the residual radiation and the activation of air and its subsequent release to the environment. The characterisation of the facility with respect to the categorisation of its various parts in terms of radioactive waste classes and their corresponding elimination pathways will be performed in the future.

Prompt radiation

The shielding of the CHARM Facility was designed to respect the CERN area classification. This means that the ambient dose equivalent rates should be below 3 µSv/h for the control rooms inside the East Hall and less than 15 µSv/h (low occupancy area) at 40 cm outside the shielding walls for maximum average beam intensity of 6.7E10 protons per second. In addition, the ambient dose equivalent rates should be below 2.5 µSv/h outside the hall for maximum average beam intensity. These requirements meant that all shielding passages (access chicanes, ventilation ducts, cable ducts) had to be designed in an optimised way. The locations of the area monitors were chosen to verify compliance with these area classification limits.

In addition, the shielding had to be designed so that the annual effective dose to members of the public, combined of prompt radiation (sky-shine) and releases to the environment, would be less than 1 µSv for the nominal annual protons on target.

The design of the shielding tried to make use of as many existing concrete and iron shielding blocks as possible as well as magnet yokes that had been part of the former LEP accelerator. In total, approximately 2000 tonnes of iron and 4000 tonnes of concrete have been used. The design had also to accommodate the fact that design choices were limited due to the presence of existing facilities in the East Experimental Area.

Monte Carlo simulations with the FLUKA code [5] [6] have been performed to estimate the prompt ambient equivalent dose rate levels for the CHARM Facility. The prompt ambient equivalent dose rate is shown at the beam-line level in Figure 6 and at 40 cm above the top of the shielding roof in Figure 7, demonstrating the compliance of the shielding design with the design goals with respect to the CERN area classification. The annual effective dose to members of the public due to sky-shine is shown in Figure 8 to be 1.25 µSv for the current design. Since this value is above the design goal of 1 µSv/y, the design of the shielding roof will be modified to respect this design goal. The predicted ambient dose equivalent rate level on the shielding roof will be verified by dedicated measurements during the commissioning of the CHARM Facility because of the large sensitivity of the ambient dose equivalent rate behind thick shielding to the uncertainties of the attenuation properties of the shielding material. This will also be part of the measurement programme for the CERN Shielding Benchmark Facility that is described below.

Figure 6. Prompt radiation at beam-line level with colour-coded area classification (blue covering the acceptable control room levels and green the acceptable low occupancy area levels)

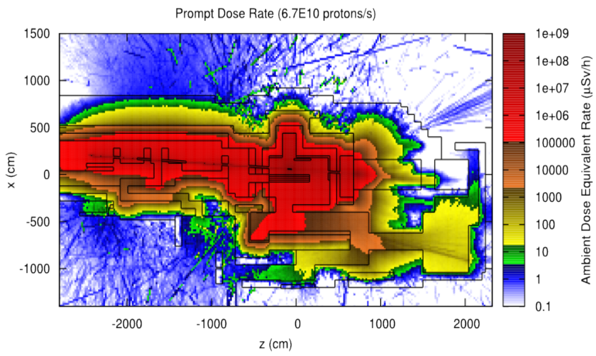


Figure 7. Prompt radiation at 40 cm above the shielding roof with colour-coded area classification (blue covering the acceptable control room levels and green the acceptable low occupancy area levels)

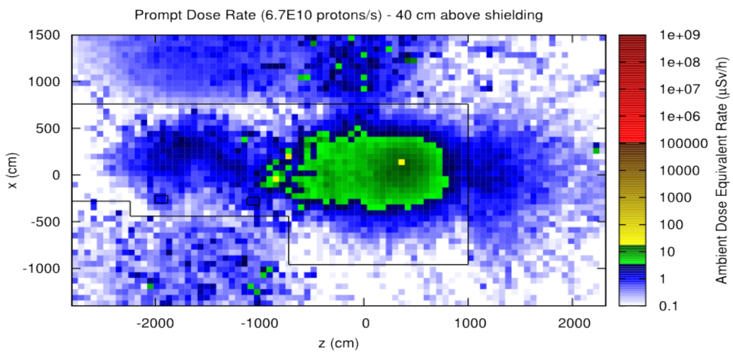
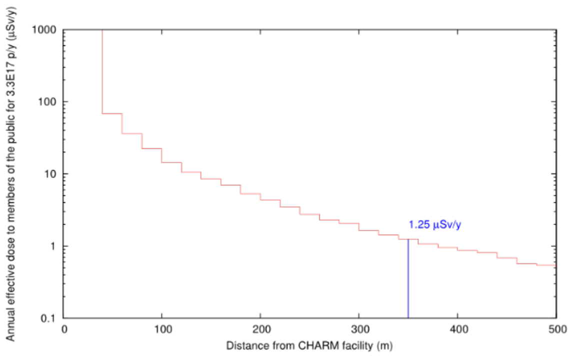


Figure 8. Annual effective dose to members of the public due to sky-shine with nominal beam parameters



Residual radiation

The reduction of the residual ambient radiation levels is an important optimisation following the ALARA principle. In addition, reducing the residual ambient radiation levels to lower, the effective dose to personnel during interventions will also decrease the administrative requirements for the interventions and, as a consequence, result in a more efficient exploitation of the facility.

The main optimisation measures have been:

- Starting from the beginning, the radiation protection assessment was integrated in the design process of the facility.
- Parts of the concrete walls and the iron ceiling structure in the vicinity of the target have been covered with marble. This will reduce the production of ^{24}Na and ^{22}Na in this area and the marble will act as a shielding material reducing the radiation from the iron ceiling structure.
- The target will be moved to a dedicated alcove during access to the CHARM Facility. This alcove will be closed by a 20 cm thick movable marble shielding reducing the radiation exposure due to the target.
- Extensive studies for different shielding configurations during access have been performed to optimise the access procedures.
- An ambient dose equivalent rate objective of 100 µSv/h for the Patch Panel area (see Figure 4) has been defined. This area will be the most frequently accessed part of the facility.

To predict the ambient dose equivalent rate levels for various operational scenarios and cool-down times, Monte Carlo simulations have been performed with FLUKA and the DORIAN code [7]. The ambient dose equivalent rate levels for 200 days of operation with maximum beam intensity followed by cool-down periods of 1 hour and 1 day are shown in Figure 9. The evolution of the ambient dose equivalent rate for the Patch Panel area for various shielding configurations is presented in Figure 10 as a function of the cool-down time. The ambient dose equivalent rates for the Patch Panel area at cooling time less than 1 day are approximately 3 times higher for the configuration where the movable shielding walls have been retracted from the facility during irradiation than for the configuration where the movable shielding walls have been inside the facility during irradiation. The objective of 100 µSv/h for the Patch Panel area can be achieved for a cooling time of 1 hour for the maximum beam intensity when the movable shielding walls have been inside the facility during irradiation and for the nominal beam intensity (lower by a factor of 3) when the movable shielding walls have been retracted from the facility during irradiation.

Figure 9. Residual radiation levels after 200 days of operation with maximum beam intensity followed by 1 hour (left) and 1 day (right) of cool-down

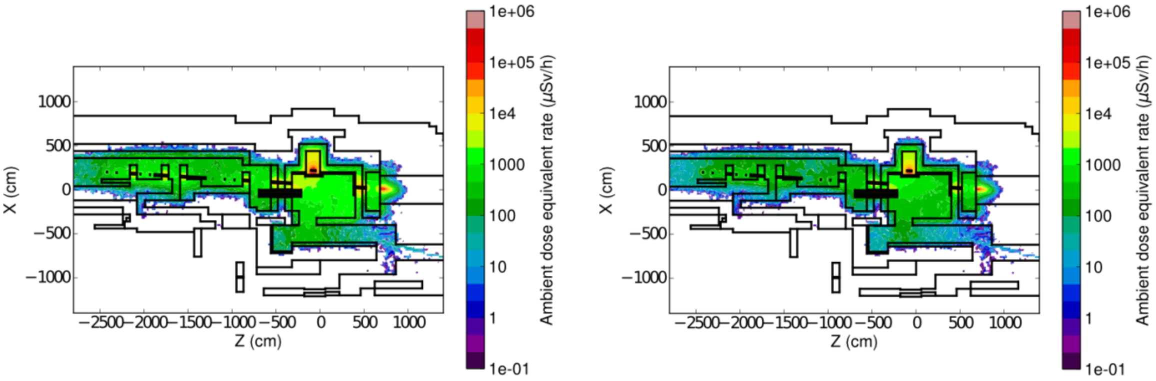
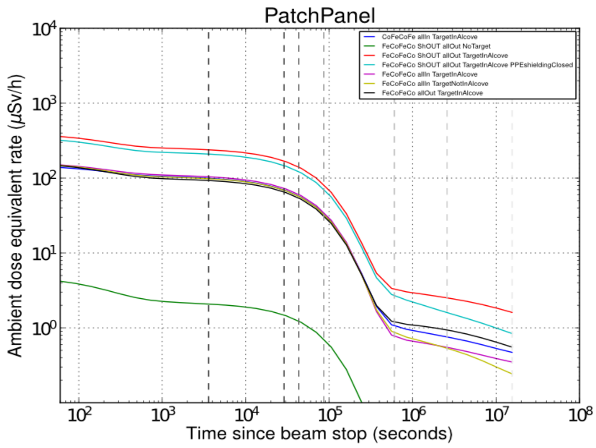


Figure 10. Time evolution of the residual radiation in the Patch Panel area after 200 days of operation with maximum beam intensity



Air activation and subsequent release to the environment

The operation of the CHARM Facility will result in the activation of the air inside the facility. The design goals for the ventilation system of the CHARM Facility are:

- The committed effective dose due to inhalation has to be less than 1 µSv for a 1-hour access. The reason for this requirement is that the inhalation component of the effective dose is not directly monitored. The external exposure due to the activated air is monitored, is not larger for the given geometries than the internal exposure and is normally much smaller than the external exposure from the activated components of the facility.

- Effective dose to members of the public (reference group) has to be less than 1 µSv per year, combined from prompt radiation (sky-shine) and from releases to the environment.

The following methodology has been used to obtain the radionuclide concentrations, the annual release to the environment and the resulting annual effective dose to members of the public:

- The track-length spectra for protons, neutron and charged pions have been scored in the air volumes inside the CHARM Facility (and the upstream proton facility) in the FLUKA Monte Carlo simulation.
- These track-length spectra have been folded with a dedicated set of air activation cross-sections [8] [9] to obtain the radionuclide production yields.
- The radionuclide concentrations in the facility and the release term to the environment have been calculated from the radionuclide production yields taking the time evolution and the characteristics of the ventilation circuit into account.
- The radionuclide concentrations in the facility after beam stop have been converted to the committed effective dose due to inhalation without flush for a 1-hour access by application of exposure-to-dose conversion coefficients for inhalation [10]. The decrease of the radionuclide concentrations due to decay during the 1 hour period has been taken into account.
- The release term has been converted to the effective dose to members of the public by application of release to effective dose conversion coefficients, computed with a dedicated Monte Carlo integration program EDARA [11].

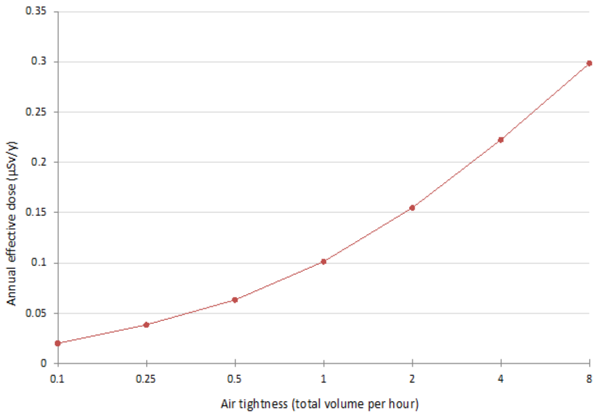
The obtained committed effective dose due to inhalation and the effective dose to members of the public are given in Table 3 for static confinement with one flush every week and dynamic confinement with an extraction rate of 1 air volume per hour. To meet design goal 1, dynamic confinement with a flush before access has been chosen. As shown in Figure 11, to meet design goal 2, the effective dose to members of the public has been calculated as a function of the air tightness, which corresponds to the extraction rate to ensure dynamic confinement of the facility. A design goal for the air tightness of 2 air volumes per hour has been set to preserve enough margin for the overall design goal of 1 µSv per year for the effective dose to members of the public (reference group).

Table 3. Radiological impact of air activation for different confinement types

Confinement type	Committed effective dose due to inhalation without flush* for 1 hour access µSv	Release to the environment TBq/y	Effective dose to members of the public µSv/y
Static (1 flush/week)	14	0.026	0.0072
Dynamic (1 volume/h)	1.9	2.4	0.10

*These are hypothetical values used only in the assessment. A flush will always be performed before access.

Figure 11. Annual effective dose to members of the public as a function of the air tightness



CERN Shielding Benchmark Facility (CSBF)

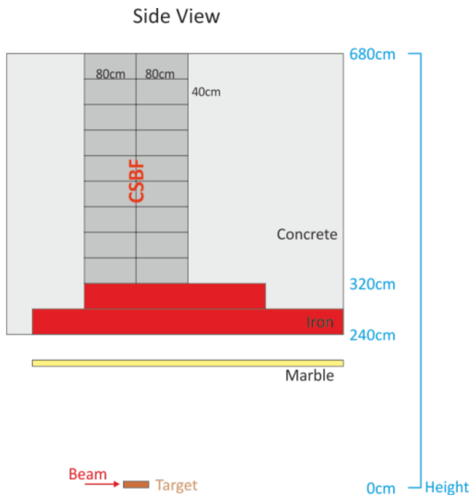
The CERN Shielding Benchmark Facility (CSBF) will be incorporated into the roof shielding structure of the CHARM Facility. The main purpose of the CSBF is the characterisation of the shielding properties of various materials for radiation fields laterally from a target after deep shielding penetration. In addition, these radiation fields can be used for detector calibration and detector inter-comparison studies.

The CSBF will make parasitic use of the radiation field generated by the impact of the beam on the CHARM target. The detailed design is still on-going and aims to minimise the impact on the operation of the CHARM Facility.

Figure 12 shows a side view and a top view of the first part of the CSBF. Situated vertically above the CHARM target and embedded into the roof shielding structure, the first part of the CSBF consists of a stack of 9 layers. Each layer is 40 cm high and consists of 2 concrete slabs of 80 cm x 80 cm area. Below the CSBF are cast iron of 80 cm thickness and marble of 10 cm thickness. The first part of the CSBF starts at a distance of 320 cm from the centre of the CHARM target. A second stack with identical layout will be placed further downstream.

Some concrete slabs can be replaced by slabs of the shielding material to be characterised. It will also be possible to place detectors inside the CSBF into hollow spaces created by dedicated support structures. These support structures will also provide cable feed-throughs. The characterisation studies of the inserted shielding materials will be performed with neutron detectors and activation samples.

Figure 12. Side and top view of the first stack of the CERN Shielding Benchmark Facility (CSBF)



Conclusions

The CERN High Energy Accelerator Mixed Field (CHARM) Facility is currently constructed in the CERN PS East Experimental Area and will provide test locations for electronic equipment with well understood, mixed radiation fields to the CERN Radiation2 Electronics (R2E) project to study radiation effects on electronic components.

The radiation protection assessment of the facility has been presented. It has been split into the shielding design for the prompt radiation, the optimisation of the residual radiation and the activation of air and its subsequent release to the environment. It has been demonstrated that the CHARM will fulfill the CERN radiation protection requirements.

The CERN Shielding Benchmark Facility (CSBF) will be incorporated into the roof shielding structure of the CHARM Facility and will make parasitic use of the beam on the CHARM target for characterisation studies of the shielding properties of various materials for radiation fields laterally from a target after deep shielding penetration.

According to the current schedule, the CHARM Facility was expected to receive beam from the PS in July 2014.

Acknowledgements

We would like to thank the team members of the PS East Experimental Upgrade project for their support.

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