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Future proton and mixed-field irradiation facilities with slow extraction for LHC operation phase and for LHC upgrades

Ralph Wolfgang Assmann[a], Jeremie Bauche[b], Markus Brugger[c], Ilias Efthymiopoulos[c], Eduard Feldbaumer[a], Mar Capeans Garrido[d], Maurice Glaser[d], Daniel Kramer[c], Lucie Linssen[d], Roberto Losito[c], Michael Moll[d], Christoph Rembser[d], Marco Silari[e], Yves Thurel[b], Emmanuel Tsesmelis[f], Helmut Vincke[e]

[a]CERN-BE, [b]CERN-TE, [c]CERN-EN, [d]CERN-PH, [e]CERN-DGS, [f]CERN-DG

1 Request to the LHCC

The main aim of the current proposal is to inform the LHCC and to seek its recognition of the scientific case for improved radiation facilities at CERN.

In particular this concerns a proton irradiation facility with slow extraction. The need for a mono-energetic charged hadron beam arises from requirements to produce a radiation environment similar to the experiments inner detectors (dominated by pions) and to gain a clearer understanding on the physics underlying the various damaging processes. The study of long-term degradation over years, readout of elements under irradiation as well as constraints arising from dead-times in radiation monitor testing make a slow extraction for this facility indispensable.

In addition this concerns a mixed field facility mimicking the radiation fields in large fluence conditions within the LHC experiments and at accelerator regions (tunnel and partially shielded areas), where irradiation is composed of a mixed spectrum. Simultaneous readout of the elements under irradiation is required for part of the tests.

The proponents put forward a possible cost-effective and unique long-term option to be implemented at CERN, whereby the both facilities are combined at a future PS East Hall location. We therefore seek support from the LHCC for pursuing implementation studies to further explore such an option.

2 Introduction and Motivation

In this proposal we present the case for future CERN-based proton and mixed-field irradiation facilities with slow beam extraction. The operation of the LHC accelerator and its detectors will be accompanied with high particle fluxes traversing equipment and detectors. Throughout the development, prototyping and construction phase of the LHC, large efforts have been put in selecting materials, components and systems that are compatible with such high radiation environments. In order to assess radiation compatibility extensive use has been made of irradiation facilities both inside and outside CERN. Radiation issues remain a concern for the operation phase, and it is important that adequate facilities are in place to verify observed behaviours at LHC and rapidly study means of mitigating any adverse effects. The preparations for the upcoming upgrades of the LHC and its injector chain require developments towards even higher radiation tolerance in many areas.

For the LHC machine radiation levels are of concern not only in the accelerator tunnel, but also in partly shielded areas close to it. Radiation levels are considerable and especially of concern for electronics which partly relies on commercial systems not designed to be radiation tolerant. A detailed analysis of these radiation levels is available on the 'Radiation To Electronics (R2E)' website [1] and constantly updated with new projections for LHC operation, as well as performed measurements. As can be seen, radiation levels range from rather low levels (< 1Gy/year and $< 10^{9}cm^{-2}y^{-1}$ annual high-energy hadron fluence) to intermediate levels (> 100Gy/year and $> 10^{11}cm^{-2}y^{-1}$) , where in the first case 'Single-Event-Effects' to commercial electronics is of main concern, and radiation tolerant design becomes mandatory in the second case. Both situations require intensified radiation testing not only when facing the present mitigation actions to be planned and optimized, but also in the mid/long-term future where these areas will always require to house certain electronics.

Most proponents of the current document are members of the Working Group on Future Irradiation Facilities at CERN [2]. The Working Group was created some two years ago on the request of several CERN department heads. At that time it became already clear that several existing irradiation infrastructures within CERN would require upgrades. In addition, there were emerging needs for new functionalities. In this context the Working Group aims at obtaining a broad overview of the requirements and a cost-effective CERN-wide approach towards the investments to be made. Maintaining complementarity with facilities outside CERN is also important. Therefore it was felt that facilities based at CERN should uniquely address irradiation needs requiring the supply of high-energy beams.

To address the needs, the Working Group carried out a broad web-based survey among users of CERN's irradiation facilities and other potential clients. The survey concentrated on facilities requiring PS or SPS beams, and it included many questions about the required irradiation properties and accompanying infrastructures. Throughout 2008 and 2009 more than 135 detailed questionnaires were filled out. At the end of 2008, the working group published its first conclusions [3], expressing the need for four different facilities:

1) Proton and ion irradiations at high energy and high density (fast extraction)
2) Proton irradiation at high intensity (slow extraction)
3) Mixed-field irradiations with slow extraction
4) Gamma irradiations in the presence of a muon beam

These conclusions have been presented at several occasions and in particular to the SPSC [4]. Of the above list, item 1) principally addresses the need to study high-energy high-density beam impacts in equipment such as LHC collimators and absorbers. Meanwhile this has resulted in implementation plans and the ongoing installation of the HiRadMat facility [5] at the TCN tunnel in the SPS BA7 area. Item 4) has led to implementation plans and an SPSC proposal to install the GIF++ gamma irradiation facility with accompanying muon beam at the H4 SPS beam line in hall EHN1 [6]. The GIF++ project currently waits complementary funding required for the final go-ahead of the planning for installation.

The current proposal addresses items 2) and 3) of the above list. As explained below, these facilities will serve both the LHC detector and accelerator communities, as well as the clients from other disciplines such as radiation monitoring. Preliminary implementation ideas have been developed. Before pursuing detailed implementation studies, the proponents seek support from the LHCC committee for the scientific case.

This proposal is timely for two reasons.

- With the foreseen end of the data taking of the DIRAC experiment in the near future and the current plans of the EN department for renovating the beam line infrastructure in the PS East Area by 2012 [7], there will be an opportunity to house a combined proton and mixed-field irradiation facility satisfying the user requirements.
- There is currently an opportunity for partial funding of such irradiation facilities within the recently approved FP7 EU project AIDA [8]. AIDA targets infrastructures for particle detector R&D and addresses a broad community of users encompassing LHC, Linear Collider, B-physics and Neutrino physics.

It is worth mentioning here, what is meant by a Facility, as opposed to a Test Area. An Irradiation **Facility** is an infrastructure that is fully dedicated to irradiation tests. It is operated by a professional team and provides calibrated and reproducible irradiation conditions to a multitude of users. Beam conditions can easily be adapted to the specific needs related to the devices under tests. Peripheral infrastructures, safety and access conditions, as well as complementary services are well optimized for irradiation test purposes. An example of a facility is the current PS East Hall facility (see section 3.1). On the contrary, a **Test Area** is generally a location where radiation conditions are met to make it suitable for performing irradiation tests. Such tests are typically performed parasitically to another primary use of the area. A **Test Area** provides opportunities for irradiation tests within the constraints imposed by its primary use, but does not meet the conditions for serving many users in safe conditions and in an optimized way.

The document is organised in the following way. In section 1 we have formulate our request to the LHCC and given an introduction and motivation in this section. In section 3 we recall the main features of the current CERN irradiation facilities for proton and mixed-field irradiations. Section 4 gives a detailed account of the results for the user enquiry for proton and mixed-field irradiations. Some recent developments, following observations made at the 2010 Chamonix workshop are also included. Section 5 reflects on the choice of operating such future facilities at either the PS or the SPS. Section 6 gives the conclusions. To provide further background information to the committee members seven appendices are included. Appendix A describes the results of fluka simulations of mixed-field irradiation spectra produced by beams of 24 GeV/c and 450 GeV/c impinging on a copper target. Appendices B to F provider further technical background and finally in Appendix G an example is given of a possible future implementation of a twin facility in the PS East hall.

3 Current Hadron Irradiation Facilities at CERN

3.1 Proton and mixed field facilities in the PS EAST HALL

The irradiation facilities in the PS East Hall (bldg. 157) are operated by the PH-DT group offering a free of charge irradiation service to all CERN Groups and Experiments. The present layout of the East Hall and the irradiation facilities is given in Figure 1. In the following a brief description of the proton and mixed field facilities is given while more details can be found in [9-11].

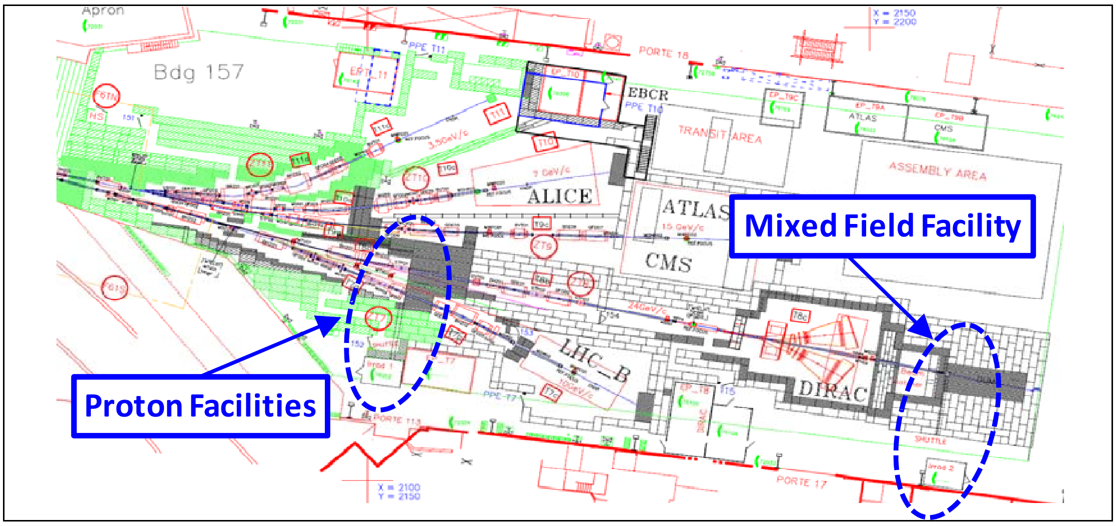


Figure 1: Layout of irradiation facilities in the PS EAST Hall (bldg. 157). Proton and mixed field irradiation areas are indicated in blue. Protons from the PS are entering the Hall from the left hand side.

3.1.1 PS EAST HALL: Proton irradiation facilities

The proton irradiation facilities are located in the T7 beam line of the PS East Hall (see Figure 1). The primary 24 GeV/c proton beam is spread and swept within an extraction time of 450 ms over a ~2x2cm^2 beam spot. A computer controlled shuttle system (IRRAD 1) allows for placing samples into the beam line without access of personnel to the primary area. Furthermore, two independent x-y-z tables carrying temperature and ambient controlled boxes (IRRAD 3 and IRRAD 7) that can be scanned over the beam are located in the T7 primary beam line area. These boxes can house bigger objects, they have however the disadvantage that an access to the primary area is needed. In all facilities samples can be electrically connected during irradiation.

- IRRAD 1 (Shuttle): Beam spot: 2x2 cm^2; Flux: 1-10 $\times 10^{13}$ p/cm^2/h
- IRRAD 3,7(Boxes): Size of boxes: 50x20x20 cm^3; Scanned area up to 400 cm^2; Flux: ~ 4 $\times$ 10^{11} p/cm^2/h (scanning over 10 x 10 cm^2)

- IRRAD 6: Characterized radiation field of backscattered particles used e.g. for Radiation monitor or SEU testing (~ max 140 mGy/h)

3.1.2 PS EAST HALL: Mixed field irradiation facility

The mixed field irradiation facility is located behind the DIRAC experiment in the T8 beam line of the PS East Hall. The primary beam is directed on a carbon (50cm) – lead (5cm) target which is embedded in a concrete wall. A cavity located behind this target is accessible via a computer controlled shuttle system and used for the irradiation experiments. The radiation field is a composure of different kind of particles (mainly fast neutrons) and strongly depending on the distance from the beam axis. Samples can be electrically connected during irradiation.

- IRRAD2 (Shuttle): Max sample size: 20x20x20 cm^3, 5Kg; Flux: 1-3 $\times 10^{11}$ $n/cm^2/h$ (1 MeV neutron equivalent flux at 50 cm from beam axis).

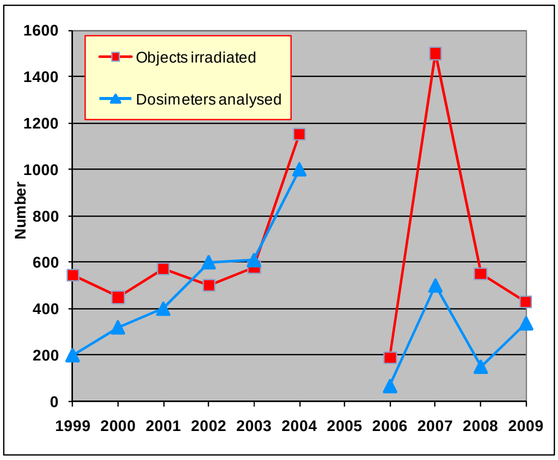
3.1.3 PS EAST HALL: Services provided by the operating team (PH-DT)

Besides the operation and maintenance of the facilities the following services are offered to clients:
Consulting and planning of the experiment: The facility staff has 18 years of experience in planning and performing irradiation experiments in the PS East Hall. Furthermore, it is strongly involved in R&D programs aiming on the improvement of the radiation tolerance of semiconductor detectors (CERN-RD48, RD50). Often custom mechanical supports for special radiation experiments are designed and/or produced for clients.
Irradiation: For simple irradiation experiments the presence of the user is not required during irradiation. Irradiations are entirely performed by the facility team. The whole irradiation procedure: User registration, irradiation request, acceptance of experiment, irradiation experiment, online and offline dosimetry results and shipping are completely transparent for the user via www-interfaces and online databases.
Dosimetry: A wide range of dosimetry measurements starting from online SEC counter monitoring to complex offline beam profiling measurements with films of different radiation sensitivity are offered. Silicon pin-diodes, RADFETs, Alanine dosimeters, OSL films, Dye films and various activation foils are used. The latter are measured in NaI or Ge spectrometers operated and maintained by the facility team. The dosimetry is under constant development as expressed in the R&D and service activity in the framework of the CERN-RADMON project. The radiation field in the neutron facility as well as the secondary particle radiation field in the proton facility (used for SEU tests) have been calculated by Monte Carlo simulations and are available for the users.
Storage: Several shielded storage facilities for radioactive materials are provided which are approved and constantly controlled by the radioprotection group. Irradiated devices can be stored under various conditions (e.g. cold and under nitrogen atmosphere).
Shipping: The facility team is only interfacing between clients and the CERN radioactive material shipping service, but is also providing several safety approved shipping containers that allow e.g. for cold and temperature monitored transport of irradiated material.
Infrastructure for electrical device characterization: The complexity of the irradiation experiments has risen over the past years and often online measurements or measurements directly after irradiation are required. Computer controlled set-ups to measure CV/IV curves and various setups for resistive online measurements are provided.

Safety: All aspects regarding general and radiation safety are closely followed up and constantly improved in close collaboration with the relevant CERN safety authorities. All irradiated materials are traced in conjunction with the radiation protection group in an online-database. For handling and manipulating activated material dedicated workplaces are available for facility clients.

3.1.4 PS EAST HALL: Irradiation experiments performed over the last years

The first irradiations were performed in 1992 in the T7 line in the framework of silicon detector developments. A strongly increasing demand for irradiation experiments around 1996 led to the development of the shuttle systems that were installed in 1998 (protons) and 1999 (neutrons). Since then the number of demands and the complexity of the experiments were further rising resulting in the installation of further counting rooms and the scanning boxes in the T7 primary area. Figure 2 gives an overview of the irradiations performed in the proton irradiation facility over the years 1999-2009. Main users have been and are the tracking detector communities of the LHC experiments.



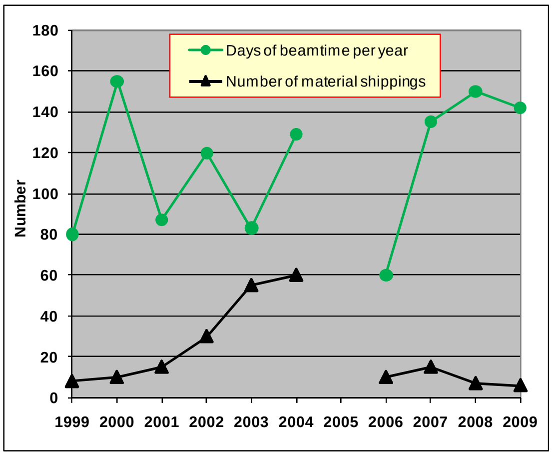


Figure 2: Number of irradiated samples and number of performed dosimeter measurements per indicated year (left). Number of days the proton facility was operated per year and number of (activated) material shipping's organized and handled through the Facility operators. In 2005 no beams were available at CERN and in 2006 the breakdown of PS magnet systems strongly reduced the available beam time.

3.1.5 Limitations of the facilities in the PS East Hall

The present PS East Hall facilities have a number of drawbacks. The proton facility is located in a primary beam area. As a result any access to the zone requires a beam stop for the whole East Area and exposure of personnel to radiation, mainly due to activated materials such as magnets but also due to a close beam dump. There is only very restricted space in the area. As a result backscattered particles superimpose over the nominal proton beam, resulting in less clean irradiation conditions. In addition it causes activation of the irradiation tables. The neutron facility runs parasitically to the DIRAC experiment, which strongly limits its flexibility. As the proton and neutron facilities sit in 2 different beam lines, they compete with each other for beam time. In case they would be sharing the same beam line, the use of beam for irradiation purposes could be better optimized.

3.2 CERF – CERN-EU High-Energy Reference Field

3.2.1 CERF – Facility layout and spectra

The CERF facility [12] (Figure 3) is installed in one of the secondary beam lines (H6) from the Super Proton Synchrotron (SPS) in the North Experimental Area.

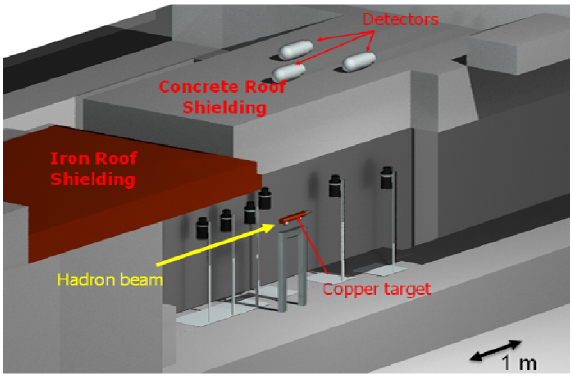


Figure 3: Layout of the CERF facility in the North Experimental Hall of the SPS as modeled in FLUKA. The side shielding is removed to show the inside of the irradiation cave with the copper target set-up

A positively charged mixed hadron beam (about 1/3 protons and 2/3 pions) with momentum of usually 120 GeV/c is impinging on a copper target, 7 cm in diameter and 50 cm in length, which can be installed in two different positions inside an irradiation cave. In the past also other beam energies between 20 GeV and 205 GeV were used. The secondary particles produced in the target traverse a roof shielding of either 80 cm concrete or 40 cm iron. In addition, laterally two shielding thicknesses are available, 80 and 160 cm respectively. On top of the roof-shields well defined radiation fields are produced over two areas of 2x2 m^2, each of them divided into 16 squares of 50x50 cm^2. Each element of these “grids” represents a reference exposure location. The energy distributions of the particles at the various exposure locations have been obtained by Monte Carlo simulations performed with the FLUKA code [13, 14]. The neutron energy distribution on top of the concrete shield shows a marked high-energy neutron component, at an energy of 10–100 MeV, resembling particle spectra at LHC underground accessible areas, as well as fairly closely the neutron field produced by cosmic rays at commercial flight altitudes, while the spectrum outside the iron shield is rather dominated by neutrons in the 0.1 – 1 MeV range.
For the Concrete and the Iron Top positions, additional muon and neutron components are present which directly come from the primary target area (TCC2) located upstream of CERF, from the H6 beam line and from the adjacent H8 line. Their intensity depends on various factors which are not under direct control, such as the intensity of secondary beams in neighboring beam lines.
The intensity of the primary beam hitting the target is monitored by an air-filled Precision Ionisation Chamber (PIC) at atmospheric pressure, placed in the beam upstream of the copper target. By adjusting the beam intensity on the target one can vary the dose equivalent rate at the reference positions, typically up to 1 mSv/h on the iron roof-shield and up to 500 µSv/h on the 80 cm concrete roof or lateral shield. Due to radiation protection reasons the beam intensity hitting the target is limited to 10^8 hadrons at 120 GeV/c.
In addition to the top shielding positions, measurement positions are also available behind the lateral side shielding of the irradiation cave as well as inside the cave around the target position. Figure 4 and Figure 5 show the particle fluence distributions for two typical irradiation locations lateral and downstream of the target (inside the shielding).

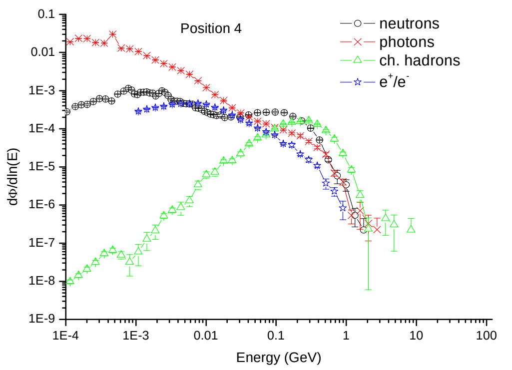


Figure 4: Typical particle fluence spectra obtained in reference position 4 lateral to the target [15].

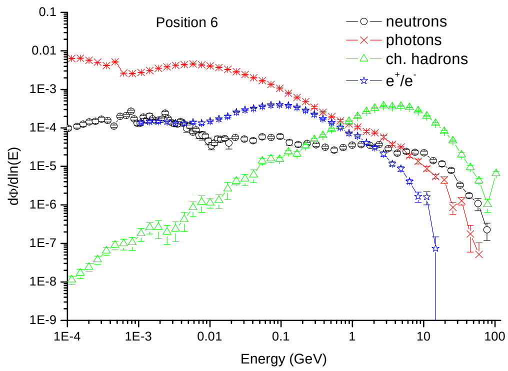


Figure 5: Typical particle fluence spectra obtained in reference position 6 downstream of the target [15].

3.2.2 CERF - Overview of experimental applications and recent experiments

Several measurement campaigns have taken place at CERF starting in 1992. Many institutions from all over Europe, as well as from the USA, Canada and Japan, have used the facility to test various types of passive and active detectors. These included devices such as high pressure ionization chambers, TEPCs, GM-counters, different types of rem counters, bubble detectors, scintillation based dose-rate meters, electronic pocket dosemeters, Si-diodes, solid state nuclear track dosemeters (SSNTD), thermoluminescent dosemeters (TLD), films, recombination chambers, multisphere systems. Although most of the beam time was dedicated to test dosimetric instrumentation, the facility has also been exploited for other uses. Experimental applications for which the facility has been used include test and intercomparison of active instrumentation and passive devices, test of active and passive dosemeters used for individual monitoring, calibration of devices before their use for in-flight measurements either on commercial flights or in space, various tests related to the LHC project, investigations of computer memory upsets and radiobiological studies. Several benchmark experiments for Monte Carlo based particle transport codes like FLUKA were also performed. Since 2003 the irradiation positions close to the target have also been used. Typical applications at this location are material activation studies and high-level dosimetry calibrations, studies of detector responses of beam loss monitors and ionization chambers to mixed high-energy radiation fields. So far, each year two weeks of beam-time were approved and shared between the users (main and parasitic).

3.2.3 Limitations of the CERF facility

The main drawback of the CERF facility can be found in the intensity limit due to dose rate constrains outside the shielding. For a beam energy of 120 GeV/c the maximum allowed intensity per cycle (16.8 s) can be found at 10^8 hadrons. Another drawback of the CERF facility is the particle background from neighboring beam lines and from the TCC2 area which is found at the Iron-Top and Concrete-Top reference positions.

3.3 CNRAD - CNGS radiation test areas

In 2007, the control electronics of the CNGS [16] neutrino target area was suffering from Single Event Effect (SEE) errors in the TSG4 side gallery. This made the operation of the facility impossible, therefore all the electronics was relocated to the TCV4 area and shielded. The empty TSG4 gallery then became a testing area for the electronics systems installed in the LHC. Its acronym is CNRAD. A comparison between the LHC and CNRAD particle energy spectra is given in Appendix E.

3.3.1 The CNRAD radiation test areas

The graphite target together with the horn and reflector located downstream are the source of the radiation. Secondary particles from the lateral shower propagate through the interconnecting ducts between the target chamber and the side gallery. The 400 GeV/c proton beam for CNGS is produced by two fast extractions from SPS in 10.5µs spaced by 50ms. The nominal annual integrated beam intensity is 4.5×10^{19} pot (protons on target). During the 2009 operation, the average beam intensity was approximately 2×10^{18} pot/week.

The test zones are concentrated around two adjacent ducts TSG45 and TSG46 (see Figure 6). When measured in the line of sight, the difference in dose and fluence rates between the ducts is roughly a factor 10. The dose rates in the test locations range from 0.2 to 30 Gy(Si)/week.

The radiation fields are very stable throughout the year as the alignment of the beam has to be extremely precise. The integrated radiation levels thus scale with the integrated beam on target intensity and each test position can be calibrated just once, which is done with the RadMon detectors and cross checked with activation foils and passive dosimeters, as well as successfully compared to detailed Monte-Carlo calculations.

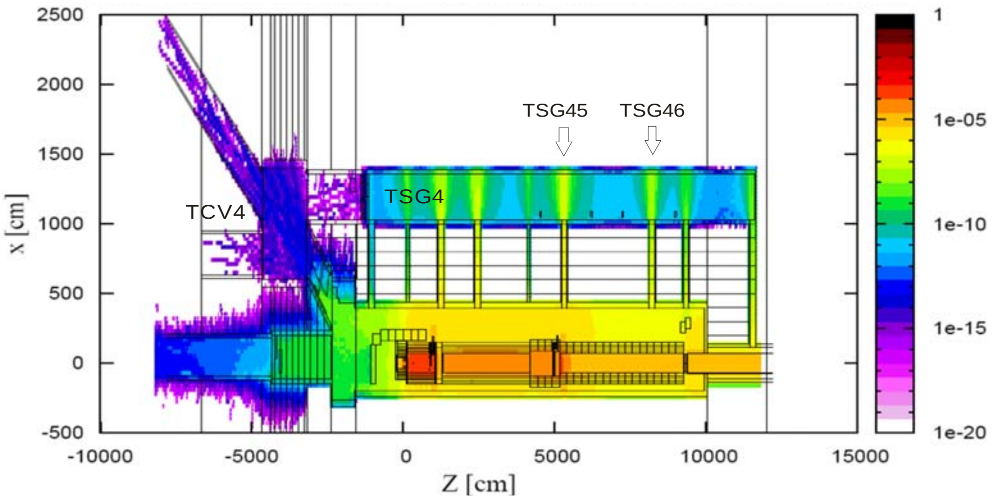


Figure 6: Fluka simulation of the high energy hadron fluence (E>20 MeV) in CNGS normalized to one primary proton on target [17]. The CNRAD test areas are marked with arrows.

3.3.2 Limitations of the CNRAD radiation test areas

The main limitation of the TSG4 side gallery when used for the electronics tests is the fact that it is a parasitic type of facility. The access to the zone is possible only during the long stops of the beam for physics, as one day cool down and air exchange is required prior to entering the irradiation area. When testing electronics, it is usually highly desirable to exchange a part of the tested device in case of a destructive event very soon after it occurs.

The access restrictions and post irradiation handling are further complicated by the trace contamination of the zone by ^{7}Be.

The accuracy of the test measurements and simulations is limited due to the presence of high radiation field gradients implied by the geometry of the area (i.e. edges of the ducts).

The combination of limited space and small number of accesses per year leads to a packaging of the devices, which significantly alters the radiation fields.

The distance of the test area from the CNGS control room, where readout electronics has to be located, is about 1.5km, which is a severely limiting aspect for many systems. This also renders the testing of water cooled systems practically impossible.

4 A survey on needs for irradiation facilities at CERN

The CERN Working Group for Future Irradiation Facilities [2] has recently carried out a survey on the demand and requirements for future irradiation facilities at CERN. Gamma, Proton, Ion and Mixed Field irradiation facilities were considered. The survey was sent to a large community of potential users. A web-based questionnaire was prepared for each type of facility addressing questions regarding the required radiation field, the facility infrastructure, the irradiation experiments to be performed, the annual required beam time and the time scale for the projects that would be performed in the facilities. In total 134 questionnaire forms were returned in 2008/2009 for the 5 irradiation facility types under consideration. Figure 7 gives the distribution of the answers received for the different facility types under consideration. Most answers were submitted for the proton and mixed field irradiation facilities indicating the interest of a bigger user community in these types of facilities.

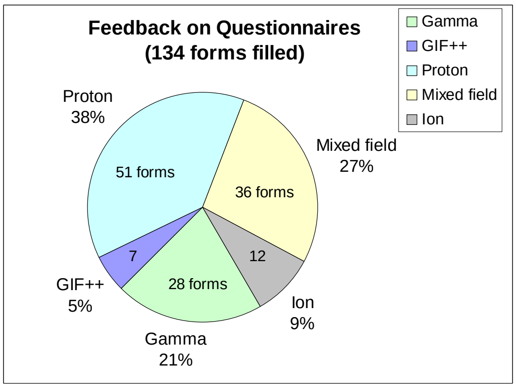


Figure 7: Distribution of answers received in the survey for the individual types of radiation facilities:

- **Proton facilities** (exposure to fast or slow extracted proton beams of PS or SPS)
- **Mixed-field facilities** (mixed particle field arising from interaction of PS/SPS proton beam with target)
- **Gamma Irradiation Facility** (radiation field of a high intensity gamma source).
- **GIF++** (Gamma Irradiation Facility combined with a particle test beam of low intensity)
- **Heavy Ion Irradiation Facility** (exposure to fast or slow extracted primary ion beams of the PS or SPS)

Feedback was obtained from a wide range of potential user communities with an equally wide range of motivations as to why perform irradiation tests. The feedback obtained in this survey allowed a rough grouping of the user into three communities:

- **Experiments:** Mainly users working on the LHC experiments, the upgrade of the LHC experiments or R&D projects related to detector upgrades relevant for the LHC upgrade.

- **Accelerator:** Mainly users working on the LHC accelerator and its upgrade or on recent concerns for radiation damage at the LHC and/or accelerators in other HEP laboratories. This includes the development of targets for high intensity beam experiments.

- **Radiation Monitoring:** Users working on radiation monitoring and radiation field simulations including benchmarking of Monte Carlo simulation tools. Mainly for radiation monitoring inside and around CERN infrastructure, but also for more generic tests of radiation monitoring devices dedicated to high energy particle detection.

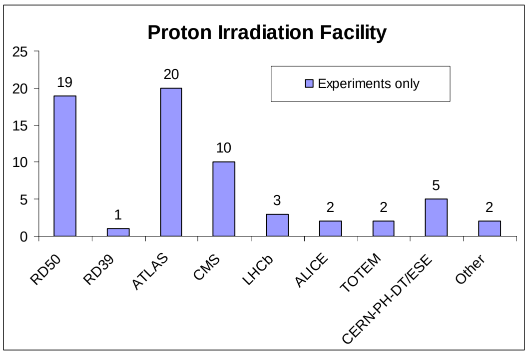
In the following two sections the feedback obtained for the proton and mixed-field irradiation facilities is summarized. A more detailed report including a detailed evaluation of the requested facilities infrastructures can be found in [18]. The third section reflects on recent requests that were not included in the 2008/2009 survey.

4.1 Survey on need for proton irradiation facilities

The conducted survey focused on proton irradiation facilities based on fast and slow extracted beams. With the recent approval of the HiRadMat facility project [5], a facility with a fast extracted beam in the SPS is now under construction. The following sections focus entirely on proton facilities with slow extracted beams.

4.1.1 User community for proton irradiations (slow extraction)

Most of the 51 feedback forms received were submitted by colleagues working on the LHC Experiments (72%), while 24% were submitted by colleagues from the *Accelerator Community* and 4% by colleagues from the *Radiation Monitoring Community*. A more detailed investigation on who answered for the *Experiment Community* is given in Figure 8. It can be deduced that most answers were arriving from the ATLAS and RD50 collaborations and that the main interest is coming from users working on the inner tracking detectors. This can clearly be understood from the fact that for the luminosity upgrade of the LHC the inner tracking detectors of ATLAS and CMS will have to be replaced with one main reason for the replacement being the radiation damage of the used silicon sensors.



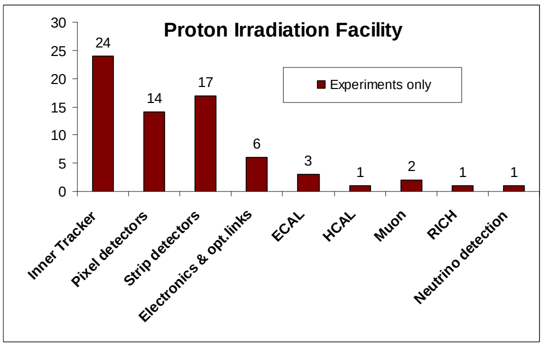


Figure 8: Questionnaires filled split up according to membership in collaborations and units of users (left) and according to detector types for which the person filling the questionnaire works. Double counting was used for persons working for several experiments or on several detector types.

4.1.2 Type of equipment and purpose of irradiation test

The feedback obtained regarding the type of equipment to be irradiated and purpose of irradiation test is summarized in Table 1 and Table 2 (more specific details are given in [18]).

Table 1.: Type of equipment intended to be irradiated in proton irradiation facilities.

Type of equipment	votes	fraction of votes (78 votes given)	fraction of questionnaires (51 forms filled)
Detector or detector component	34	43.6%	66.7%
Material (generic)	20	25.6%	39.2%
Accelerator component	10	12.8%	19.6%
Radiation monitor or dosemeter	7	9.0%	13.7%
Other	7	9.0%	13.7%

Table 2.: Purpose of irradiation experiment intended to be irradiated in proton irradiation facilities.

Purpose of irradiation experiment	votes	fraction of votes (74 votes given)	fraction of questionnaires (51 forms filled)
Radiation hardness test	40	54.1%	78.4%
Detector and equipment performance test	21	28.4%	41.2%
Dosemeter calibration	4	5.4%	7.8%
Other	9	12.2%	17.6%

The size of the objects to be irradiated is an important parameter. The following results were obtained from the survey:

Approximate area to be exposed to the radiation field (51 replies)

19	(37.3%)	Very small, less than about 2 cm x 2 cm
26	(51.0%)	Small, less than about 10 cm x 10 cm
4	(7.8%)	Medium, less than about 25 cm x 25 cm
2	(3.9%)	Large, less than about 1 m x 1 m
0	(0.0%)	Very large, more than about 1 m x 1m

In conclusion most of the objects to be irradiated are expected to be smaller than 10 cm x 10 cm and 88% of all users require an irradiation area of less than 10 cm x 10 cm. In a proton beam facility this usually means that the object to be irradiated has to be scanned through the beam.

4.1.3 Requested beam parameters and radiation levels

Proton beam energy - A clear preference to 24 GeV/c protons (slow extraction)
Given the option to chose between a radiation facility using 24 GeV/c protons or 450 GeV/c protons, 55% of the users coming from the *Experiments Community* would prefer to use the 24 GeV/c protons while 45% would not have any preference. None of the users preferred to use the 450 GeV/c protons. The 24 GeV/c protons are preferred for various reasons. For many present and prior users of the PS irradiation facilities the possibility of keeping the well known proton energy also for the future seems to be very attractive solution. Future experiments could be compared to data taken in the past with the same particle energy. The main argument, however, is the fact that most of the protons in the LHC Experiment's particle spectra have below GeV energies. Radiation tests performed with 24 GeV/c protons give therefore more realistic damage predictions than tests performed with 450 GeV/c protons, which represent a negligible fraction of the proton spectrum in the LHC Experiments. This latter argument was for 4 colleagues from the CMS/ECAL, ALICE and CMS/Tracker collaborations strong enough to exclude the use of 450 GeV/c protons for their specific experiment.

Radiation levels and number of required protons
The fluence range of interest to the users is indicated in the form of a histogram in Figure 9. The user requiring more than 2×10^{16} p/cm^2 are aiming for material studies on target materials, close to beam accelerator materials as collimators or to extreme high level dosimetry applications. The maximum particle fluence requested by the Experiments Community was 2×10^{16} p/cm^2, corresponding to the maximum fluence for pixel detectors in LHC Experiments with an integrated luminosity of about 3000fb^{-1}.

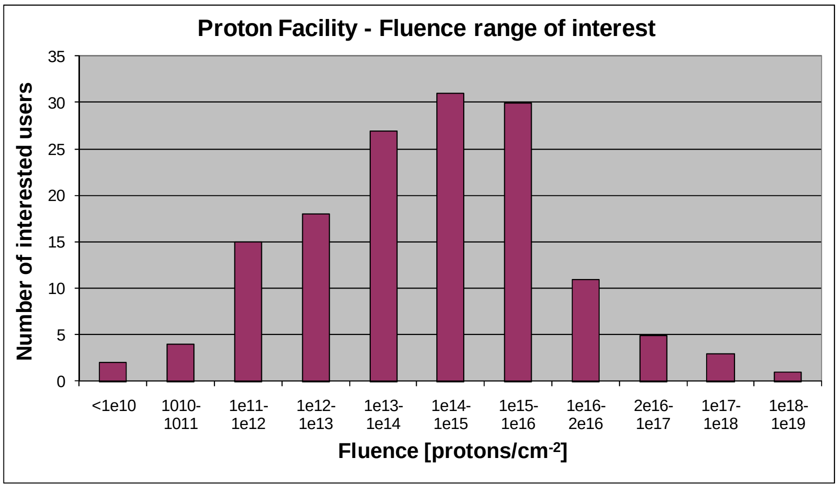


Figure 9: Number of users requesting to be able to perform irradiations in the indicated proton fluence range. The fluence is given in units of particles/cm^2 as requested by the users asking for homogeneous irradiations over their objects.

4.1.4 Conclusions on proton facilities beam parameters

Having the choice between 24 GeV/c protons and 450 GeV/c protons, the experiments community would prefer to use 24 GeV/c protons with a slow extracted beam while for many of the irradiation tests also 450 GeV/c protons could be used. However, some experiments testing for example more massive detector components like calorimeter crystals would be excluded or more difficult to understand when using 450 GeV/c protons. A fluence of $2x10^{16}$ p/cm^2 with a homogeneous beam profile over about 5 cm^2 should be reached in no longer than 2 weeks to cover the majority of the user requests.

4.2 Survey on need for mixed field irradiation facilities

4.2.1 User community for mixed-field irradiations

In total 39 feedback forms were received. A splitting of forms according to the user communities introduced previously is given Figure 10 while Figure 11 indicates that feedback was obtained from CERN staff as well as CERN users. The majority of the answers (54%) was received from colleagues working on radiation monitoring which in this context comprises activities related to radiation detector applications, radiation detector and dosemeter test and calibration and benchmarking of Monte Carlo simulation tools, which are partly related to the LHC project.

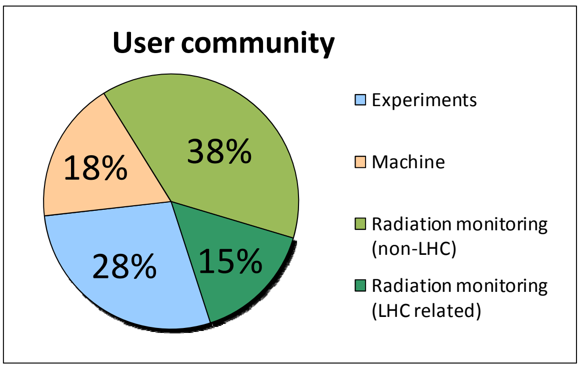


Figure 10: Splitting of the 39 forms according to user communities.

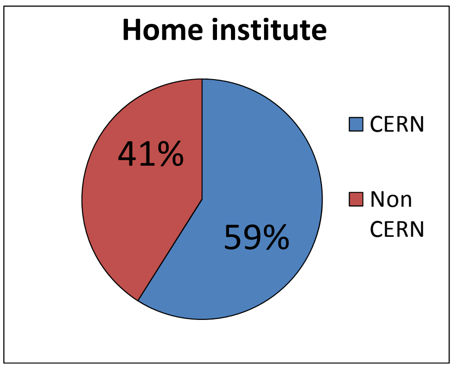


Figure 11: Splitting of answers according to home institute of users requesting the facility.

The feedback from the Experiments Community was submitted mainly by users working on the LHC experiments and the LHC experiments upgrade. Colleagues from ATLAS, CMS, LHCb, TOTEM, RD50 and CERN-PH-DT and PH-ESE members answered to the questionnaire.

4.2.2 Type of equipment and purpose of irradiation tests

The feedback obtained regarding the type of equipment to be irradiated and purpose of irradiation test is summarized in Table 3 and Table 4 (more specific details are given in [18]).

Table 3: Type of equipment intended to be irradiated in the mixed-field irradiation facilities.

Type of equipment	votes	fraction of votes (59 votes given)	fraction of questionnaires (39 forms filled)
Detector or detector component	25	42.4%	64.1%
Accelerator component	5	8.5%	12.8%
Material (generic)	6	10.2%	15.4%
Radiation monitor or dosemeter	18	30.5%	46.2%
Other (please specify details below)	5	8.5%	12.8%

Table 4: Purpose of irradiation experiment intended to be irradiated in mixed-field irradiation facilities.

Purpose of irradiation experiment	votes	fraction of votes (59 votes given)	fraction of questionnaires (39 forms filled)
Radiation hardness test	14	27.9%	43.6%
Detector and equipment performance test	19	31.1%	48.7%
Dosemeter calibration	21	36.1%	56.4%
Other	3	4.9%	7.7%

The size of the objects to be irradiated is an important parameter. The following results were obtained from the survey:

Approximate area to be exposed to the radiation field (39 replies)

- 3 (7.7%) Very small, less than about 2 cm x 2 cm
- 12 (30.8%) Small, less than about 10 cm x 10 cm
- 14 (35.9%) Medium, less than about 25 cm x 25 cm
- 9 (23.1%) Large, less than about 1 m x 1 m
- 1 (2.6%) Very large, more than about 1 m x 1m

In conclusion most of the objects to be irradiated are expected to be smaller than 25 cm x 25 cm. However, an important feature of any mixed field facility will be to accommodate also objects with sizes of the order of $1m^3$ which were requested by 25% of the users filling the feedback form. The last point is especially important for accelerator electronics which partly has to be tested in a full rack configuration (e.g. power-converters). This community requires often radiation fields behind a concrete shielding (like shielded areas in the LHC machine) over a large volume.

4.2.3 Requested mixed-field parameters, radiation levels and beam times

Primary proton beam energy – No clear preference for 24 GeV/c or 450 GeV/c

In the questionnaire the possible choices for the proton momentum hitting the production target were limited to the two values of ~ 24 GeV/c and ~450 GeV/c. Additionally, it was possible to indicate if both energies would be equally well suited for the intended experiment or if one option would be excluded. The response to the question “What would be your preferred proton energy?” was that 60% do not have any preference, while 23% would prefer a SPS location and 18% a PS location. However, 92% stated that either energy could be used for their experiments. 450 GeV/c was excluded only once, 24 GeV/c two times. However, three strong preferences were requiring radiation fields behind shielding and in all three cases no muon radiation was required. Since the energy and particle distribution of radiation fields behind shielding is very similar for both energies except for the muon component directly downstream the target (see Appendices A and B), all strong preferences can most likely be fulfilled by either energy. In conclusion there is no strong preference for either energy, as long as the available number of protons can fulfill the demands for the requested integrated particle fluence.

Requirements on integrated dose and neutron fluences

The users were asked to specify the minimum and maximum neutron fluence they would require for their experiments. Fluences and doses requested range up to $2x10^{16}$ n/cm^2 and 10^7 Gy respectively. In order to obtain a maximum fluence/dose value which can be achieved in a mixed radiation field a correlation between maximum fluence/dose and the surface/volume to be irradiated has to be considered. In a beam-on-target situation the fluence/dose values received close to the target are significantly higher than those which are available at larger distances to the beam impact point. On the other hand a homogenous fluence/dose value close to the target can be guaranteed only over a small area/volume. In other words: the size of the area which can be irradiated homogenously is correlated with the maximum achievable fluence/dose.

An estimate for the maximum achievable fluence/dose was calculated as a function of the irradiation position around a copper target (length: 50 cm, diameter: 7cm) (see Appendix A and Appendix D). The results presented in Table 5 are given for a primary beam momentum of 24 GeV/c and an intensity of $2x10^{16}$ protons per week of beam operation. Applying a 450 GeV/c beam instead of a 24 GeV/c beam by keeping the total number of protons would result in dose and fluence values which are approximately 10 times higher than those obtained by a 24 GeV/c beam operation.

Table 5: Dose, 1 MeV equivalent neutron fluence and high-energy hadron fluence (> 20 MeV) as a function of the irradiation position around the target. These estimates are based on a 24 GeV/c proton beam impact on a 50 cm long copper target and a weekly intensity of $2x10^{16}$ protons. All results except those of the last line are FLUKA results (details see Appendix D).

Position	**Size**	**Dose**	**1 MeV equiv**	**hadrons >20 MeV**
		Gy per week	**n/(cm^{2}week)**	**had/(cm^{2}week)**
Target end position	2x2cm^2	1.1E+06	1.9E+15	1.7E+15
50 cm downstream the target	2x2cm^2	7.3E+04	1.3E+14	2.3E+14
Target side position	2x2cm^2	1.8E+05	2.1E+15	7.7E+14
20 cm lateral to the target	10x10cm^2	3.1E+04	1.8E+14	5.6E+13
50 cm lateral to the target	25x25 cm^2	6.9E+03	4.1E+13	1.3E+13
1.5 m lateral to the target	1x1m^2	9.0E+02	5.3E+12	1.5E+12
3.5 m lateral +1 m concrete shield (extrapolated from the 1.5 m value)	Minimum 1x1m^2	1.8E+01	1.1E+11	3.1E+10

Dose/fluence requirements versus irradiation area: Using a weekly beam intensity of $2x10^{16}$ protons at 24 GeV/c or $2x10^{15}$ protons at 450 GeV/c the minimum requirements of almost all users can be fulfilled. The maximum desired dose/fluences or flux/ dose rate can be delivered for about two third of the users (for more details see [18]). Most of the users requiring a large irradiation area do not have high dose/fluence requirements. One important group of users, who require large irradiation areas, can be found in the LHC machine community. Tests of electronics close to the target or behind shielding are the main applications for this group. In order to test whole electronic racks or power converters under LHC irradiation conditions, for most cases dose/ fluence values are required which can be easily delivered by the aforementioned irradiation of a copper target.
The majority of users who ask for high dose/fluence require an irradiation area of less or equal 10x10 cm^2. For users aiming to irradiate with radiation levels corresponding to the innermost Pixel Layers of a luminosity upgraded LHC (approx. 2×10^{16} n/cm^2), a 10 times higher intensity or an irradiation time of 10 weeks (valid for irradiation positions close to the target) would be required.

4.3 Recent developments not included in the survey

The radiation induced failure of equipment at CNGS, the operational stop of the facility and the requirement to relocate electronics and install adequate shielding, triggered a respective evaluation for the LHC. For the latter, the situation is significantly more complex then what was encountered at CNGS: more areas and a huge amount of equipment (different types and high number) are affected. As a consequence, the 'Radiation To Electronics' (R2E) Study Group [1] was formed and is leading all related activities since then.

Radiation levels are less severe in the machine as compared to the experiments (ranging for total ionizing dose from 1-100Gy/year and high-energy hadron fluences in the order of 10^8-$10^{11}cm^{-2}y^{-1}$). A detailed summary of the various radiation levels, as well as their evolution as a function of LHC operation phases is available on the R2E website [1].

Given the complexity and scale of the areas and equipment involved, R2E first focused to analyze in detail the situation, foresee immediate short-term measures and prepare certain medium-term solutions. This process also included dedicated radiation tests (following the area and equipment priorities established in the first place). Short- and medium-term actions were implemented and the detailed analysis process also includes various long-term options, which are the current focus of the Study Group.

In this context, radiation tests could so far be carried out at outside facilities (for components and electronics card testing), as well as at the CNRAD facility (see section 3.3). However, as already mentioned earlier, both cases have certain short-comings, especially when facing test requirements for large volumes, rather low radiation levels and unpredictable failure processes. What concerns test requirements, both a comparison to what has been measured at CNRAD so far, as well as the taking into account the number of concerned CERN equipment groups, show a multiple annual request of integrated fluences in the order of $10^{12}cm^{-2}$, in many cases in multiple periods. Each of these tests, partly seeks different intensities and test conditions, as well as has special test requirements (*e.g.*, water cooling, complex rack configurations).

For this and in a more general sense for radiation test requirements, one can subdivide radiation effects in electronic devices into two main categories: cumulative effects and 'Single Event Effects (SEE)'. The steady accumulation of defects causes measurable effects that can ultimately lead to device failure. Stochastic failures, so-called 'Single Event Effects' (SEE) form an entirely

different group as they are due to the direct ionization by a single particle (from nuclear reaction in the electronics itself), able to deposit sufficient energy through ionization processes in order to disturb the operation of the device. They can only be characterized in terms of their probability to occur, which will strongly depend on the device as well as on the flux and nature of the particles.
In the current configuration, LHC alcoves equipped with commercial or not specifically designed electronics are mostly affected by the risk of SEEs. Electronics installed in the LHC tunnel was mostly designed for the expected radiation levels and will also suffer from accumulated damage. In both areas, mixed radiation fields of various particle types and a large range of energies are the source of radiation. Moreover, especially in shielded areas (e.g., UJs, RRs) an important contribution to the total particle fluence is coming from low-energy or thermal neutrons, possibly becoming an important additional source of 'Single Event Upsets (SEU)'.

At present, a large number of equipment and electronics is exposed to radiation around the various LHC areas. Many of these equipments were not specifically designed to be radiation tolerant, thus pose a certain risk to LHC operation. The preparation and study of long-term mitigation actions requires a careful analysis of various aspects:

- radiation levels
- inventory of installed electronics and failure consequences
- expected radiation sensitivity
- early monitoring and optimization possibilities
- mitigation options

Radiation testing of electronics (existing, adopted and newly developed) will be of high importance during this analysis procedure, as well as along the entire mitigation project. In addition, future demands to install electronics in LHC radiation areas are likely, thus again demanding for respective radiation testing.

The multitude of different equipment and electronics, the fact that most of the systems are based on commercial electronics, as well as the limited option for a comprehensive radiation tolerant design, also define the respective test requirements and environment. Radiation tests dominantly aim for full system tests under the following conditions:

- rough estimate of system radiation sensitivity (e.g., important for existing electronics in order to get a rough estimate as from when onwards problems might occur)
- verification of intermediate system improvements (e.g., remote reset possibilities for existing equipments)
- new development of electronics (based on radiation tolerant components) and their final system test

For all cases, a radiation test in a mixed field as close as possible to the actual LHC environment is of clear advantage. The current radiation areas of concern for the LHC can be divided in two groups: (a) tunnel area and (b) shielded areas. Figure 12 and Figure 13 show the respective radiation fields which are compared in Appendix E to the CNRAD radiation field.

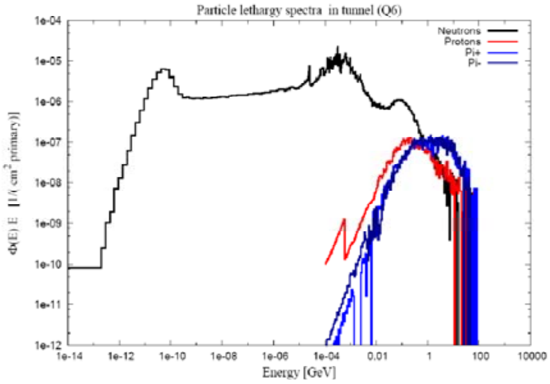


Figure 12: Particle energy spectra as seen by electronics installed in the LHC tunnel.

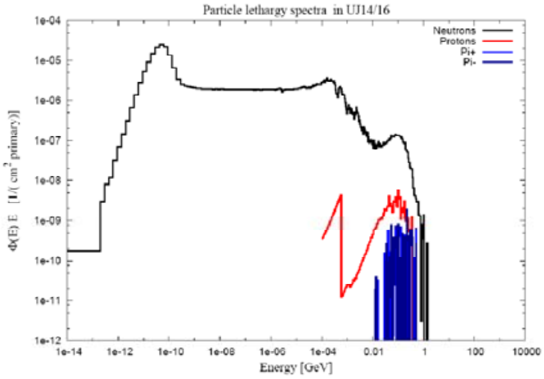


Figure 13: Particle energy spectra as seen by electronics installed in shielded LHC areas close to the tunnel.

In contrary to component testing and selection for small systems (following standardized test procedures), the impact on cost and time does not allow a similar approach for many areas and equipment of the LHC. In this sense, any radiation test facility for mixed particle energy spectra shall provide a radiation field as close as possible to the one the electronics is actually exposed to. CNRAD provides this to a high degree and we can conclude that any new facility should provide similar if not better coverage of typical radiation fields, as well as overcome the current radiation test shortcomings of CNRAD (see section 3.3).

The irradiation facility spectra shown in Appendix A will be together with the proton rates of PS and SPS (see Appendix C) able to provide the required irradiation conditions within reasonable time. A comparison between the LHC spectra and the spectra occurring in the surroundings of a copper target irradiated with a 24 GeV/c proton beam was already presented to the SPSC and is also summarized in the Appendix F.

5 Possible options for implementation and operation

As indicated in section 1, the main aim of the current document is to seek recognition by LHCC for the scientific case for proton and mixed-field irradiation facilities. Besides carrying out the enquiry described in section 4, and drawing conclusions about requirements for future irradiation facilities at CERN, the working group has already made several studies related to the choice of options for implementation and operation. We felt that it was useful to share the resulting information with the LHCC. For this purpose, we include 7 appendices with more detailed technical information in the current document:

Appendix A: Mixed radiation fields from 450 GeV/c and 24 GeV/c protons
Appendix B: Shielding considerations for mixed-field facilities
Appendix C: Estimates on available number of protons at PS and SPS locations
Appendix D: Dose and fluence calculation for mixed-field arriving from 24 GeV/c protons
Appendix E: Comparison between the CNRAD and LHC particle energy spectra
Appendix F: Comparison between the CERF++ and LHC particle energy spectra
Appendix G: Potential upgrade of the PS East Hall facilities

In this section we recall the principal outcome of these studies and reflect on resulting options for implementation.

A central question for the implementation of an irradiation facility at CERN is the choice between a PS or SPS location. For the proton facility, this question has been addressed in consultation with the users. As explained in section 4.1.4, a larger number of satisfied proton users are served at a PS location.

For the mixed-field facility, the choice between PS and SPS is more complex, as several competing factors come into play. The simulation study of mixed-field spectra reveals that the principal composition and energy-spectrum of the particles emerging from a copper target at 24 GeV/c and 450 GeV/c are similar. One of the main spectral differences is a pronounced presence of high-energy muons downstream of the target at 450 GeV/c. The fluence intensity and the dose rate produced per primary particle are about a factor of 10 higher in case of the 450 GeV/c beam impact. Unfortunately the suppression of the muon tail in compliance with safety regulations behind a 450 GeV/c facility will be difficult. As a consequence, and in order to profit from the higher rates at the SPS, a downstream location has to be found or alternatively an implementation has to be conceived where the outgoing muon beam is deviated in a safe (typically below-earth) direction. On the contrary, at a PS location, the lower-energy muon tail offers more straightforward shielding implementation options. Concerning the potential number of protons available at PS East Hall and SPS North Area locations, it can be said that these are of the order of 1.5×10^{17} per year at the PS. Similar intensities could be reached at the SPS North Area[*]. As a consequence, the flux and fluence needs for proton irradiations are well satisfied at the PS and SPS, with the longest irradiations estimated to take about 5 weeks. At the PS typical proton irradiations are carried out with several samples placed behind each other in the beam without loss of performance, therefore a large number of users can be served. For mixed-field irradiations the number of available protons are largely sufficient at the SPS, while at the PS the flux and fluence requirements are just sufficient. The longest irradiations will take some 10 weeks at the PS, while several users can be served at the same time by exploiting several locations surrounding the target.

As already mentioned in section 2, the foreseen end of the data taking of the DIRAC experiment in the near future and the current plans of the EN department towards renovating the beam line infrastructure in the PS East Area seem compatible with the implementation of a combined proton and mixed-field facility by 2013-2014. This idea is a bit further elaborated in Appendix G. On the other hand, the SPS North Area is currently in high demand, and finding the necessary space and beam time for a future mixed-field facility in EHN1 seems less obvious.

In view of the above, we seek support from the LHCC for pursuing implementation studies to further explore a combined option in the PS East Area.

Concerning the future operation of such a facility, we propose a model that is similar to the operation of the current PS East Hall irradiation facilities (see Section 3.1). The PH department, PH-DT group, currently provides the operation of these facilities. The PH department intends to maintain this type of service for the experiment's community also in the future. As a future facility is likely to serve both the experiment and accelerator communities, a new model will be

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[*] These numbers are based on the estimate given in Appendix C. It should be noted that the PS irradiation facilities actually received in 2008 and 2009 about 1.5×10^{17} protons/year, while a more realistic estimate for the available number of protons in a potential SPS facility are assumed to be much lower than the indicated 1×10^{17} protons/year. Radiation protection (shielding) issues as well as the beam sharing with several other users will significantly decrease this number. The present CERF facility in the North Area has for example a bunch intensity which is by 3 orders of magnitude lower than the one assumed in the calculation (see Appendix C).

worked out, preferably involving the deployment of resources from both communities for the operation of the facility.

While waiting for the construction of such a new facility, urgent tests on LHC accelerator equipment (see section 4.3) can be performed at CNRAD or, in case of intermediate intensities, at an ad-hoc test area requiring adaptations to an SPS beam area.

6 Conclusions

In the present proposal we have presented the need for improved proton and mixed-field irradiation facilities with slow beam extraction at CERN. Strong needs are expressed by both the detector and accelerator communities and concern the LHC operation era as well as the upgrades of machine and experiments. The current facilities and test areas have a number of limitations and drawback. Preliminary studies by the working group indicate that there are possibilities for a coherent and cost-effective approach towards improved facilities for the future.
The aim of this document is to inform the LHCC and seek its recognition for the need of such facilities. In addition we would appreciate the support of the LHCC for pursuing further implementation studies at a PS East Hall location.

Appendices

A. Mixed radiation fields from 450 GeV/c and 24 GeV/c protons

Based on a work by E.Feldbaumer and H.Vincke (CERN-DGS/RP)[19].

This chapter presents the comparison between the radiation fields emerging from a proton beam impact on a copper target at a momentum of 24 GeV/c and 450 GeV/c. The target is cylindrically shaped with a length of 50 cm and a diameter of 7 cm. In the FLUKA simulations it is placed in the target position of the so called CERF++ area, which is a simulation study of an irradiation facility (see Figure 14 left side). The area close to the target is foreseen to be used as high dose irradiation area, which is exposed to the high-energy particles emerging directly from the target. The inner part of CERF++ is surrounded by a shielding construction made of concrete and iron. Behind the shielding a second irradiation area is located. The radiation fields in this area are defined by the shielding material between the measurement location (iron or concrete) and by the angle between the beam direction and the axis which is defined by the target position and the measurement location outside the shielding. In general, the radiation fields located downstream the target show a strong component of high-energy particles, whereas locations located lateral and upstream the target are rather dominated by the low-energy component emerging from the particle cascade. In order to compare the two scenarios 12 locations have been chosen to elaborate the differences in the various radiation fields. These locations are presented in Figure 14 (right side).
The comparison of the two scenarios is based on a beam intensity of 10^{11} protons for the 24 GeV/c and 10^{10} protons at 450 GeV/c which is sent onto the target within a cycle period of 16.8 seconds (called spill). Considering these intensities equivalent radiation conditions in terms of dose rates are created at most measurement locations.

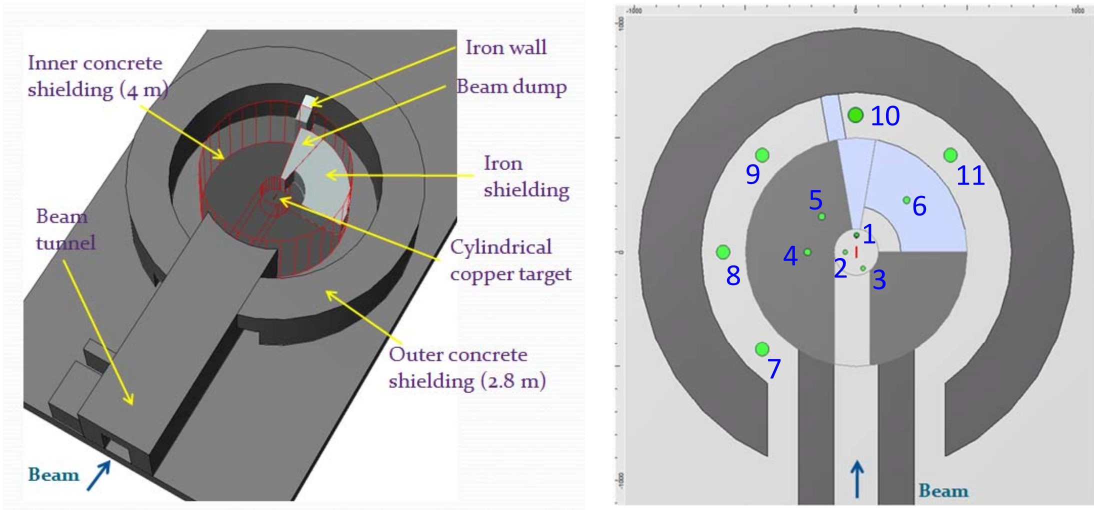


Figure 14: Layout of the CERF++ radiation field simulation study (left site) and hypothetical measurement positions chosen for the radiation field comparison between 24 and 450 GeV/c proton irradiations. The right picture shows the locations (green circles) used for the comparison of the radiation fields.

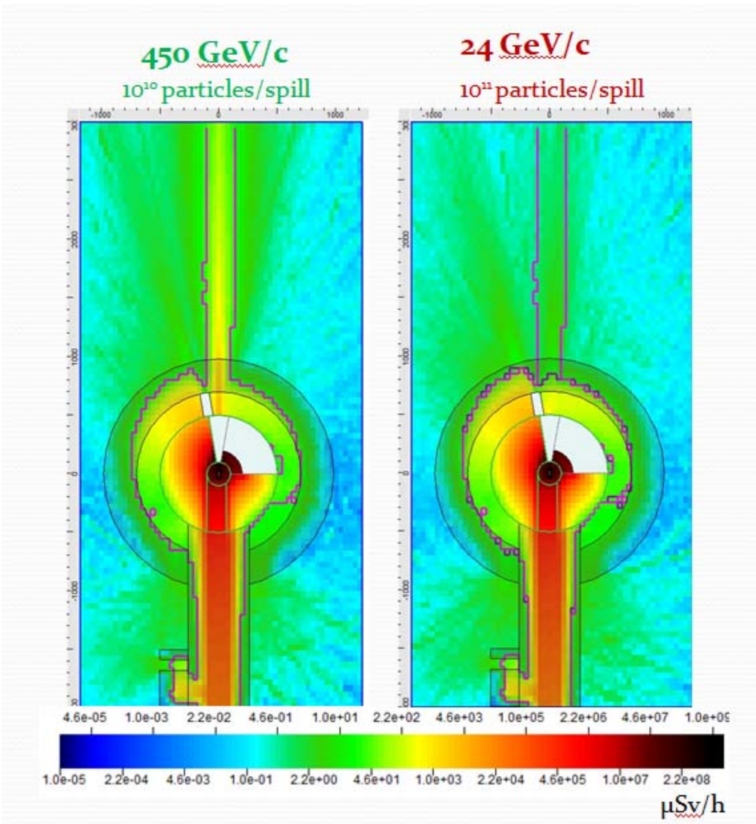


Figure 15: Cross section through the CERF++ area showing the dose rate at beam height. The purple contour line in the 450 GeV/c picture indicates the areas of a dose rate of 15 uSv/h. The blue line in the right picture serves the same purpose for the 24 GeV/c picture. To compare the two scenarios, the purple line is also displayed in the right plot.

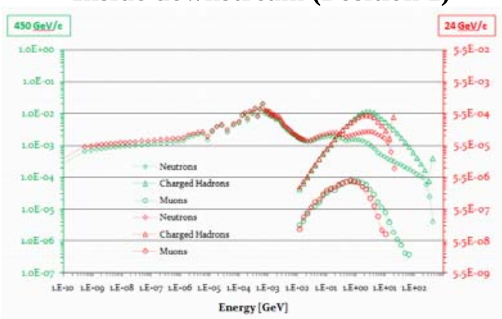
Results

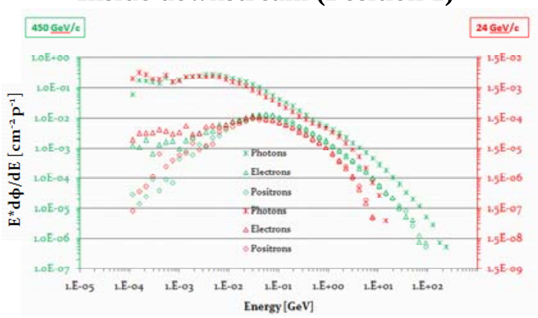
Figure 15 presents the comparison of the dose rates that were calculated for the 450 GeV/c and the 24 GeV/c beam impacts. The result of the 450 GeV/c scenario was scaled with a beam intensity of 10^{10}p/16.8s, whereas the dose rate color plot of 24 GeV/c beam impact was scaled with a 10 times higher intensity.

The comparison of the two color plots shows clearly that the dose rate conditions are very similar for both cases lateral and upstream the target position. In forward direction behind the iron dump a much higher dose rate can be found for the 450 GeV/c primary beam. The dominance of the 450 GeV/c scenario can be explained by the production of high-energy muons capable to penetrate thick shielding walls without being absorbed. In the right picture of Figure 15 contour lines (purple and blue) indicate the locations with dose rates of 15 uSv/h for the two different scenarios. Also here a resemblance of the two radiation fields in the lateral and upstream direction and the distinction in the forward direction can be found.

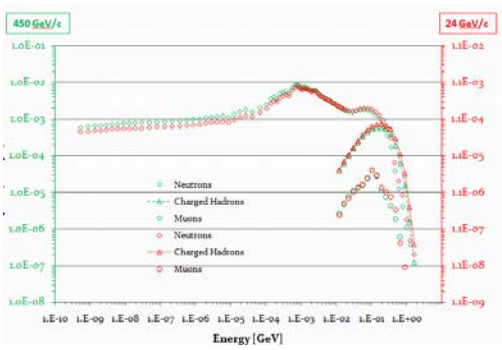
Figure 16 presents the comparison of the fluence spectra at the measurement positions 1, 2, 8 and 10 (see Figure 14: , right picture).

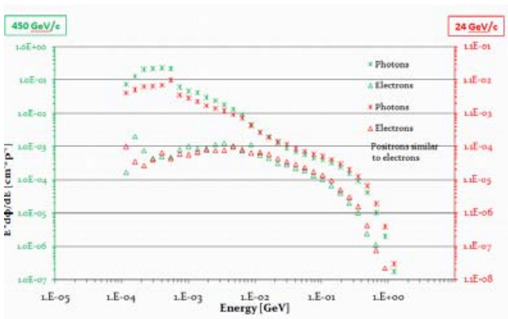
Inside downstream (Position 1) **Inside downstream (Position 1)**





Inside lateral (Position 2) **Inside lateral (Position 2)**





Outside downstream (Position 10) **Outside lateral (Position 8)**

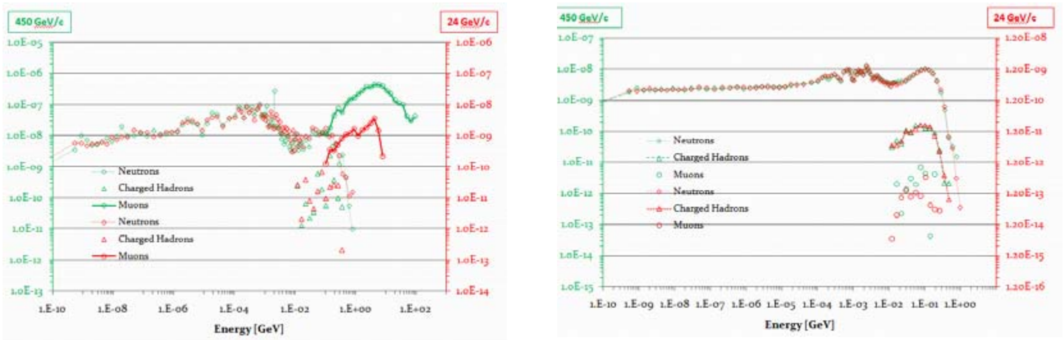


Figure 16: Comparison of the radiation fields seen at the measurement positions 1, 2, 8 and 10 emerging from the two different scenarios. The fluence scale, normalized to particles per primary proton, is displayed on the left side of the pictures for the 450 GeV/c case and on the right side for the 24 GeV/c scenario.

A more detailed comparison of the various fluence spectra shows the following results:

Inside downstream (position 1): The hadronic and muon fluences originating from the 24 GeV/c beam differ from their 450 GeV/c counterparts above an energy of several 100 MeV. Also the electromagnetic particle cascades observed at these locations show a clear dominance of the high-energy particles in case of the 450 GeV/c scenario. As expected the maximum energy of the fluences at this location can be found at the respective primary beam energy. Hence, the spectrum emerging from the 450 GeV/c beam impact ranges up to this momentum, whereas the spectra of its counterpart scenario end at 24 GeV/c.

Inside lateral (position 2): Both the electromagnetic and the hadronic cascades emerging from the 24 GeV/c and the 450 GeV/c scenario show strong resemblances.

Outside downstream (position 10): At the outside downstream position a strong muon components arises in the case of the 450 GeV/c scenario. The spectra of other particles than muons show strong similarities in case of the two different primary beam energies. This strong dominance of muons emerging from the 450 GeV/c beam impact result in a creation of a well defined muon field at this location. However, this strong muon component is also leading to radiation protection problems since muons at high energies are not subject to the strong interaction force. Hence, for a significant attenuation of the muon beam very thick shieldings are required. E.g.: to eliminate a muon with an energy of 100 GeV an iron shielding of a thickness of 70 m would be needed.

Outside lateral (position 8): Both the electromagnetic and the hadronic cascades emerging from the 24 GeV/c and the 450 GeV/c scenario show strong resemblances.

The particle fluence spectra at all other measurement locations (3 -7, 9 and 11) show very similar shapes for the two different energies.

Conclusion

A beam-on-target radiation facility using a 24 GeV/c proton beam will produce particle fluence spectra which are similar at most locations to the ones emerging from a 450 GeV/c proton facility. Only the positions located downstream the target show significant differences in the high-energy ranges of the fluence spectra. Behind the 4 m thick iron shielding, which is located downstream the CERF++ target, a strong muon component can be found in the 450 GeV/c scenario. This "muon field" is not present in the 24 GeV/c irradiation setup.

B. Shielding considerations for mixed-field facilities

Based on a work by H.Vincke (CERN-DGS/RP) [20].

For a weekly rate of 2E16 protons at 24 GeV/c a beam intensity of 5.6E11 protons per 16.8 s (considering a 100% beam efficiency) has to be received from the accelerator. In case of a beam availability of 80% a beam intensity of 7E11 protons per 16.8 s has to be considered to reach the aforementioned required weekly intensity.

The accessible area around the irradiation facility will be classified as Supervised Radiation Area. This area classification is bound with a maximum dose rate of 15 uSv/h for non-permanent access and a maximum dose rate of 3 uSv/h for permanent work places. In order to respect these dose rate restrictions a lateral minimum shielding strength of approximately 5 to 6 m of concrete is required. The same shielding strength has to be considered for a 450 GeV/c beam with a tenth of the beam intensity of the 24 GeV/c operation.

In order to estimate the shielding constrains for a 450 GeV/c and a 24 GeV/c beam at downstream locations of the target, the muon spectra at measurement position 10 (see Figure 14, Appendix A) were used as base information. For both energies the muon spectra at this location can be found in Figure 16. The fluence-to-dose conversion for high-energy muons (> 1GeV) is ~300 pSvcm^{-2}. A multiplication of the integrated muon fluence with the fluence-to-dose conversion factor results in the muon dose at this location.

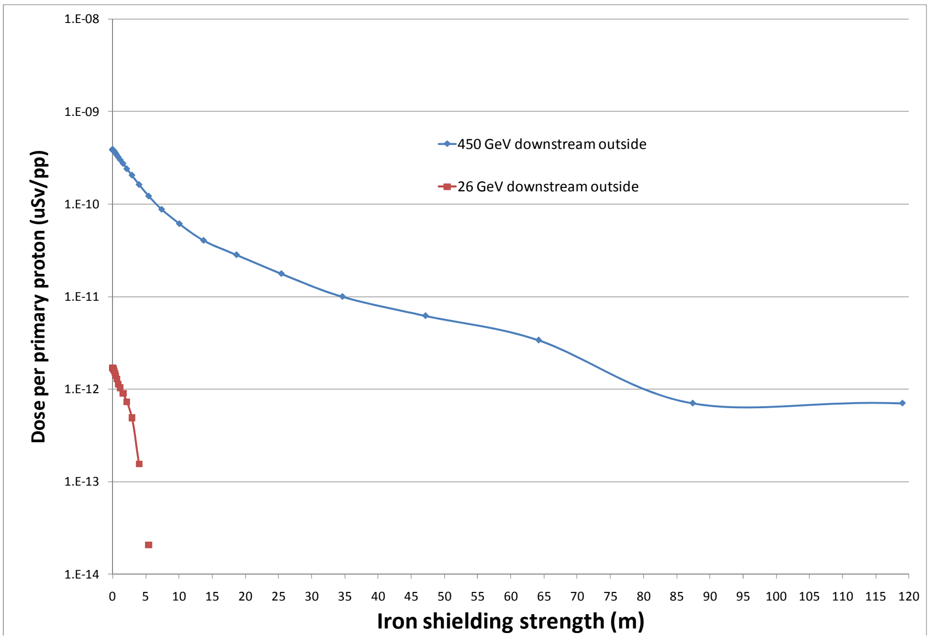


Figure 17: Muon dose outside the CERF++ installation as a function of additional iron shielding thickness added to the 4 m iron dump (see Position 10 in Figure 14). Note: the calculation considers a collimated muon beam without dispersion.

In order to reduce the muon energy by 1 GeV 0.7 m of iron or 1.8 m of concrete is needed. By the use of additional shielding a well defined part of the low-energy part of the muon spectrum will be stopped in the shielding. This results also in a reduction of the dose as a function of shielding thickness. The correlation of iron shielding thickness and muon dose obtained per primary proton-on-target can be found in Figure 17. However, one has to note that this calculation can be only seen as an estimate since the dispersion with distance of the muon beam is not considered.

By using a beam intensity of 1.5E14 protons/h (=7E11*3600/16.8) and the information given in Figure 17, an additional iron shielding thickness of 5 m of iron is required to reduce the dose to about 3 uSv/h behind the CERF++ (see Figure 14) iron dump.

The current muon shielding installation in the east hall (8.8 m iron + 1.6m concrete +2 m of iron) should be sufficient to attenuate muon radiation sufficiently.

Using for CERF++ a SPS installation, a beam intensity of 1.5E13 protons@450 GeV per hour would be required. Figure 17 clearly shows that the muon dose emerging from this installation cannot be attenuated sufficiently within several tens of meters of iron shielding. Additional measures would be required to reduce dose down to acceptable values.

Conclusion

The radiation emerging lateral to the beam impact point can be shielded with approximately 5 -6 m of concrete to comply with Supervised Radiation Protection Area restrictions. This statement is valid for both the 24 GeV/c and the 450 GeV/c beam. In order to attenuate sufficiently the muon radiation component downstream the target installation, the current PS east hall shielding will be sufficient. In case of the SPS a very long iron shielding will be required to attenuate the muon radiation level to a dose level, complying with RP rules applied to Supervised Radiation Areas, or other solution shall be applied, such as directing the muon flux to a below earth location.

C. Estimate on available number of protons at PS and SPS locations

Protons from the PS and the SPS are delivered to a number of experimental facilities and beam lines. The PS delivers protons to the East Area with up to 5 beam lines operating in parallel, to the anti-proton decelerator (AD) and its four experiments, to the n-TOF facility and serves as injector for the SPS. The SPS provides protons to the LHC, the CNGS facility and the experiments and beam lines in the North Area. Thus the flux of protons in a given beam line very much depends on needs and the priority given to the other accelerators, experiments and beam lines and the estimation given here are very rough and should be seen as a guidance for the order of magnitude of the expected flux only.

In the following, the annual proton flux at three different locations is estimated (East Area, North Area and CNGS). The basic assumptions to estimate the proton flux are:

- 50 days of beam time per year with an efficiency of 100%;
- A Super-Cycle has a length of 35 basic periods (42 seconds) and includes 9 cycles for the EAST HALL (18 basic periods), a fixed-target cycle with a long flat-top (extraction over 9.6 seconds) and other cycles for LHC, n-TOF, MD, etc..

East Area – PS – Proton flux (slow extraction)

The following assumptions are made: 6 East-C cycles per Super-Cycle with beam energy of 24 GeV/c and intensity of $2.5x10^{11}$ particles per pulse (ppp) are directed to an irradiation facility;

- Calculations for 6 pulses per CPS of 42s to an irradiation facility:
  $6\times2.5\cdot10^{11}$[ppp]×1/(42 [s])× 50[days] × 24[hours] × 3600[s] = 1.5×10^{17} [p/year] (50 days)

In conclusion about $1.5x10^{17}$ protons could be expected per year (about $2.2x10^{16}$ p/week). In case the beam from the PS would be extracted at a lower energy of 20 GeV/c, a PS irradiation cycle could be shorter (1.2s instead of 2.4s) and a factor of 2 in the proton flux might be gained.

Note that in 2008 and 2009 the PS Proton Irradiation facilities operated for about 150 days per year and received about $1.5x10^{17}$ protons per year.

North Area – SPS – Proton flux at EHN1 (slow extraction)

The maximum number of protons per extraction over one fixed-target cycle with a long-flat top is 2.4×10^{13} protons. These protons need to be shared between the various North Area targets to guarantee that all experiments (COMPASS, NA62,…) and beam lines (H2, H4, H6, H8) will get the required number of particles. For this estimation it is assumed that 10% of the beam could be available for an irradiation facility.

- Calculations for 1 spill per CPS of 42s to an irradiation facility:
  $2.4\cdot10^{13}$[ppp] × 1/(42 [s]) × 50 [days] × 86400 [s] × 10% = 1.1×10^{17} [p/year] (50 days)

Therefore about $1.1x10^{17}$ protons could be expected per year. It has however to be noted that in any surface hall for reasons of radiation protection this limit should not be reached and it is expected that one will be restricted to a much lower number number.

Note: The present CERF facility is limited to 10^8 hadrons per bunch.

CNGS (fast extraction)

The proton flux towards the CNGS target is adjusted to the physics needs of the neutrino experiments in the Gan Sasso laboratory and is defined to be $4.5x10^{19}$ protons per year. In 2009 the CNGS experiment received 3.5×10^{19} protons.

D. 24 GeV/c protons: Dose and fluence calculation for mixed-field

In order to obtain accurate information about the radiation field parameters a potential irradiation places around a copper target (length: 50 cm, diameter: 7 cm) FLUKA calculation were carried out. The simulation geometry iused can be found in Figure 18.

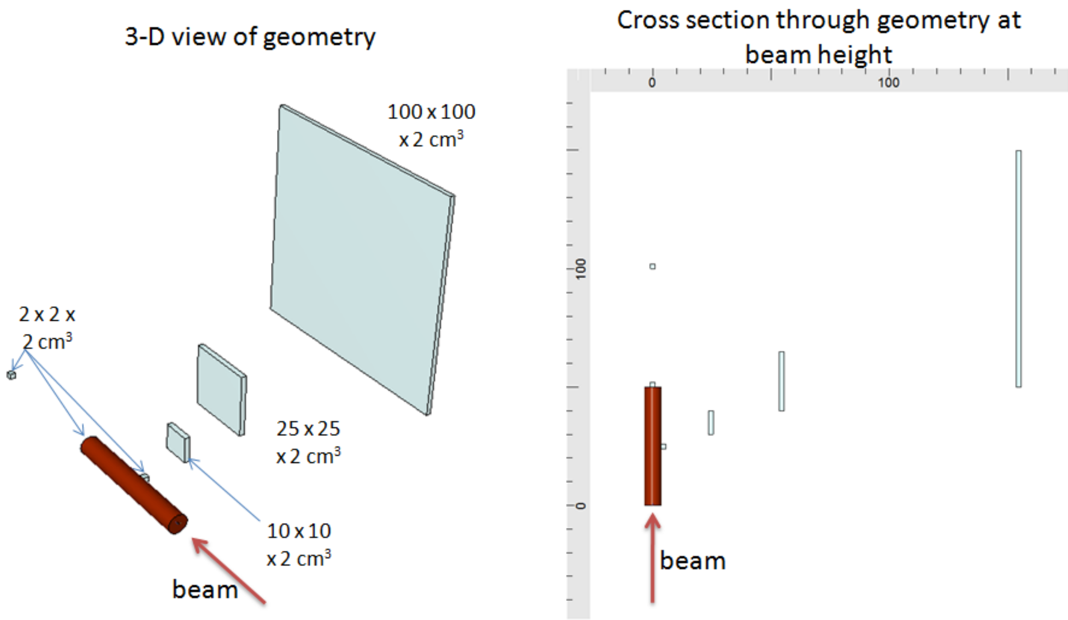


Figure 18: FLUKA geometry used to simulate the radiation field around a copper target irradiated with a 24 GeV/c proton beam. The gray areas show the various irradiation locations.
The characterization of the various irradiation locations and the dose and fluence results can be found in Table 6.

Table 6: Parameters of the irradiation positions located around the target. The dose/fluence values are quoted per primary proton hitting the copper target.

Position	**Size**	**Dose**	**1 MeV equiv**	**hadrons >20 MeV**
Target end position	$2x2cm^2$	5.4E-11	9.5E-02	8.54E-02
50 cm downstream the target	$2x2cm^2$	3.6E-12	6.7E-03	1.16E-02
Target side position	$2x2cm^2$	8.8E-12	1.0E-01	3.86E-02
20 cm lateral to the target	$10x10cm^2$	1.5E-12	9.2E-03	2.80E-03
50 cm lateral to the target	$25x25\ cm^2$	3.4E-13	2.0E-03	6.29E-04
1.5 m lateral to the target	$1x1m^2$	4.5E-14	2.6E-04	7.69E-05
3.5 m lateral +1 m concrete shield (estimated)	Minimum $1x1m^2$	9.0E-16	5.3E-06	1.54E-06

E. Comparison between the LHC and CNRAD particle spectra

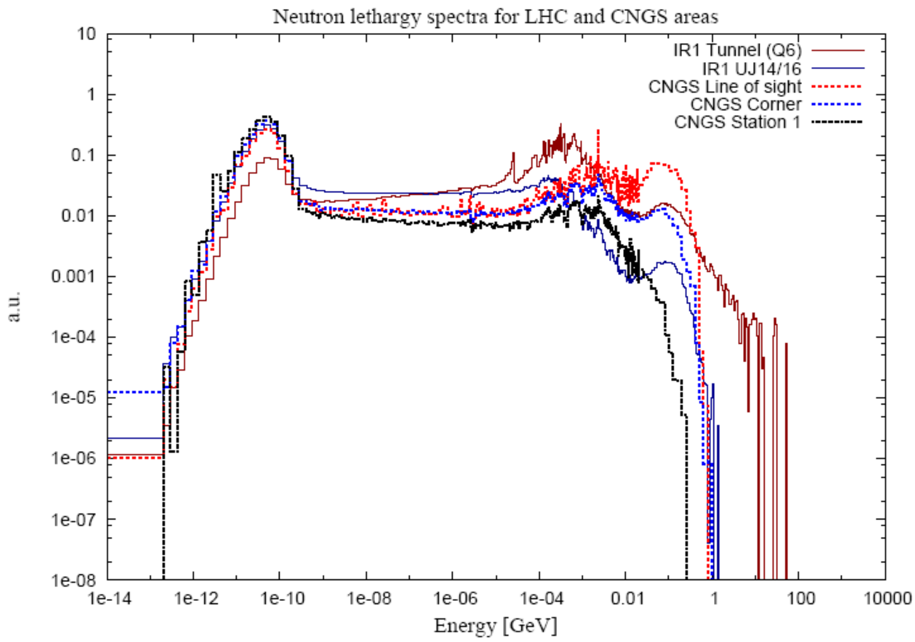


Figure 19: Particle energy spectra as seen by electronics installed in the LHC tunnel and compared to the CNRAD test locations.

Table 7: Exemplarily analysis of particle energy spectra for LHC locations (tunnel and shielded area locations). Please note that results are given as absolute fluences per primary lost particle, thus absolute values can not be directly compared. However, the composition of the mixed particle field, as well as the energy ranges of interest can be compared relative to each other and show the representative case of CNRAD.

Area	Location	>20 MeV hadrons			5-20 MeV neutrons	Thermal neutrons	R	Max. Energy
		All hadrons	Neutrons	% n				
LHC	Tunnel (Q6)	3.95E-06	2.60E-06	66	1.26E-06	1.30E-05	3	80 GeV
LHC	UJ14/16	2.88E-07	2.79E-07	97	1.40E-07	4.88E-05	169	1 GeV
CNGS	Line of sight	1.90E-07	1.84E-07	97	5.70E-08	6.20E-07	3	700 MeV
CNGS	Corner	4.30E-09	4.20E-09	98	2.70E-09	1.30E-07	30	700 MeV
CNGS	Station 1	2.80E-11	2.69E-11	96	9.30E-11	2.10E-08	750	250 MeV

F. Comparison between the CERF++ and LHC particle spectra

Spectra inside the LHC accelerator

Figure 20 presents a comparison between the fluence to be expected at irradiation position 2 of the conceptual design of the CERF++ facility (see Figure 14) and the fluence spectra calculated for the LHC tunnel environment. Strong similarities for neutrons and charged hadrons can be found. Since the spectra of both cases show almost identical shape, strong similarities behind shielding (e.g.: LHC shielding versus shielding wall beside target) can be assumed for the two cases.

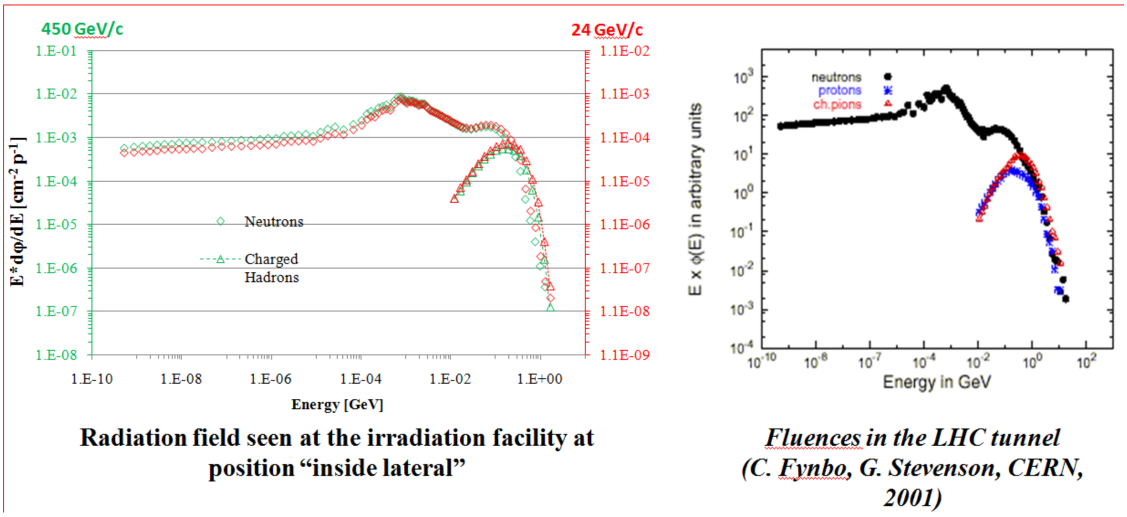


Figure 20: Comparison between the particle spectra at the lateral position (see position 2 in Figure 14) beside the copper target of the CERF++ facility and the fluence spectra of the LHC tunnel.

G. Potential upgrade of the PS EAST HALL Facilities

Figure 21 shows a recent proposal for the layout of a renovated East Area [7].

Figure 21: Proposal for a renovated East Area presented by L.Gatignon (CERN-EN) at the IEFC 2010 Workshop [7].

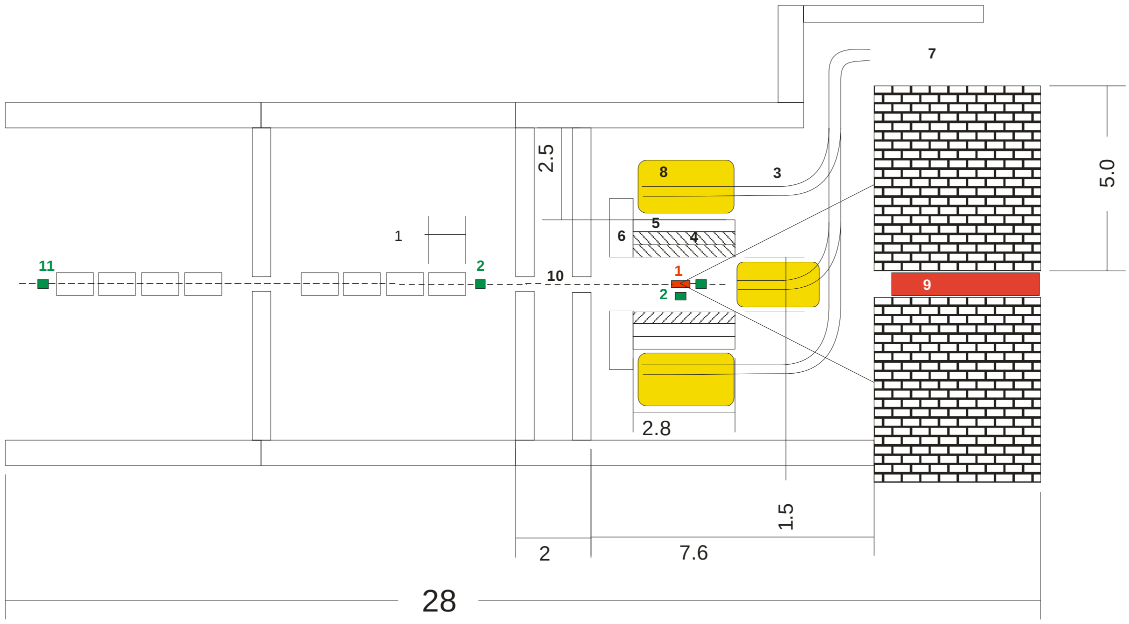


Figure 22: Schematic irradiation facility layout combining a proton and a mixed field irradiation facility.

Figure 22 gives a "back-of-the-envelope" sketch on how a combined proton and mixed field facility in the PS East Area could look like, if constructed in the present DIRAC location. The proton beam would first pass two proton irradiation areas holding each a number of x-y-z movable tables and a shuttle system (11) being able to remotely place smaller objects into the beam. The first area would be used for light materials, while the second area would be used for heavier materials producing secondary particles. Finally the proton beam would enter the mixed-field irradiation area, where it is impinging on the target (1). Around the target further shuttle systems (2) would be placed. A rail system (3) would allow to place big and heavy objects into different positions (e.g. downstream of target, or behind shielding of different thickness and material). In this sketch it is assumed that the present T7 beam dump (9) could be reused after adding some additional shielding.
Please take into account that these are only first thoughts regarding an implementation. In order to proceed towards serious implementation plans, first the scientific case of this LHCC proposal has to be recognized.

Acknowledgements

We like to thank Miguel Angel Marquina (CERN-IT/DI) for setting up and maintaining the online questionnaire web sites. His help was essential in getting the statistical overview presented in section 4.

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