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], *Mar Capeans Garrido*[d], Maurice Glaser[d], Daniel Kramer, Lucie Linssen[d], *Roberto Losito,* Michael Moll[d], *Christoph Rembser*[d], *Marco Silari*[e], *Emmanuel Tsesmelis*[f], *Helmut Vincke*[e], *Thijs Wijnands*[c]

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

1 Executive Summary

2 Introduction and Motivation

PS East Area renovation [1] (Do not remove reference, cross referenced later)

Approval of AIDA proposal [2]

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 PH-DT and are a "PH-Department Common Project" 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 [3-5].

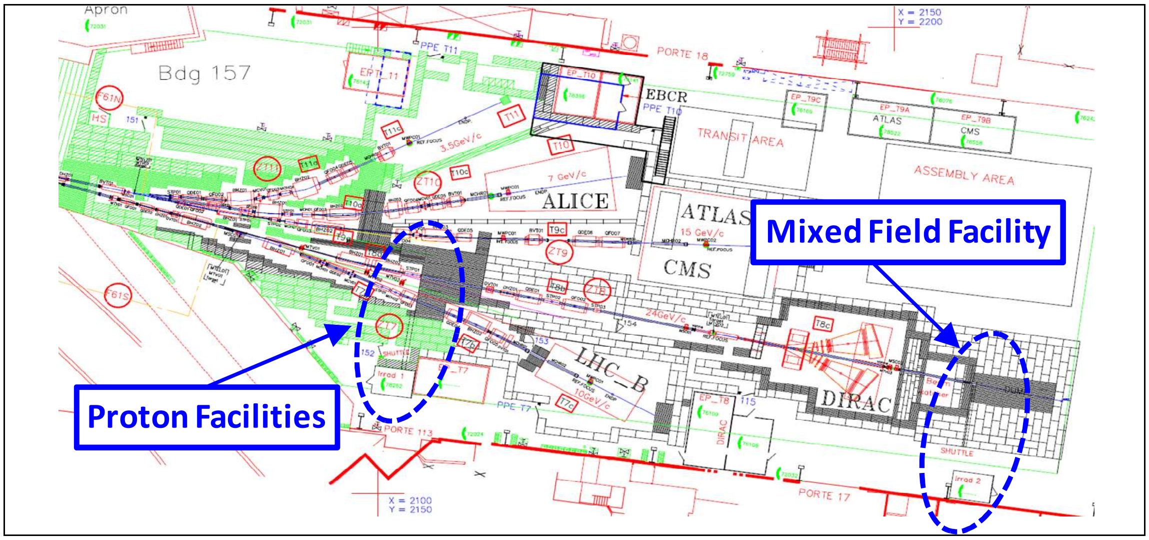


Figure 1: Layout of irradiation facilities in the PS EAST Hall (bldg. 157). Proton and mixed field irradiation areas are indicated in blue. Protons from the PS are entering the Hall from the left hand side.

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 personal to the primary area. Furthermore, two independent x-y-z tables carrying temperature and ambient controlled boxes (IRRAD 3 and IRRAD 5) that can be scanned over the beam are located in the T7 primary beam line area. These boxes can house bigger objects, have however the disadvantage that an access to the primary area is needed (implying a beam stop for the whole East Hall and exposure of personal to radiation). 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 (Box): Size of box: 50 x20x20 cm^3; Scanned area: 400 cm^2;
  Flux: 1-10 $\times$ 10^{11} p/cm^2/h
- IRRAD 5 (Box): Size of box: 2 times 15 x 15 x30 cm^3; Scanned area:49 cm^2;
  Flux: 8-80$\times 10^{11}$ p/cm^2/h
- IRRAD 6: Characterized radiation field of backscattered particles
  used e.g. for Radiation monitor or SEU testing (~100-500 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) – iron (30cm) block. A cavity located behind this block 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: 30x30x35 cm^3, 5Kg;
  Flux: 3-10 $\times 10^{11}$ $n/cm^2/h$ (1 MeV neutron equivalent flux).

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 Optically Stimulated Luminescence (OSL) films 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. The good relation with the shipping service is e.g. expressed by the fact that the database and web-interface that tracks the status and validity of radioactive material handling licenses of outside CERN institutes has been written by the facility team.

- **Irradiations outside of CERN:** Due to the involvement of the irradiation team in various R&D projects, a close network with other complementary irradiation facilities outside CERN has been established. Upon request irradiation campaigns outside of CERN are organized (e.g. pion irradiations at the PSI Villingen or neutron irradiations at the nuclear reactor at the Jozef Stefan Institute, Ljubljana or the fast neutron source at Louvain-La-Neuve).

- **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. Since 2001 the facilities are a *Common Project* of the PH-Department. Figure 2 gives an overview about 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.

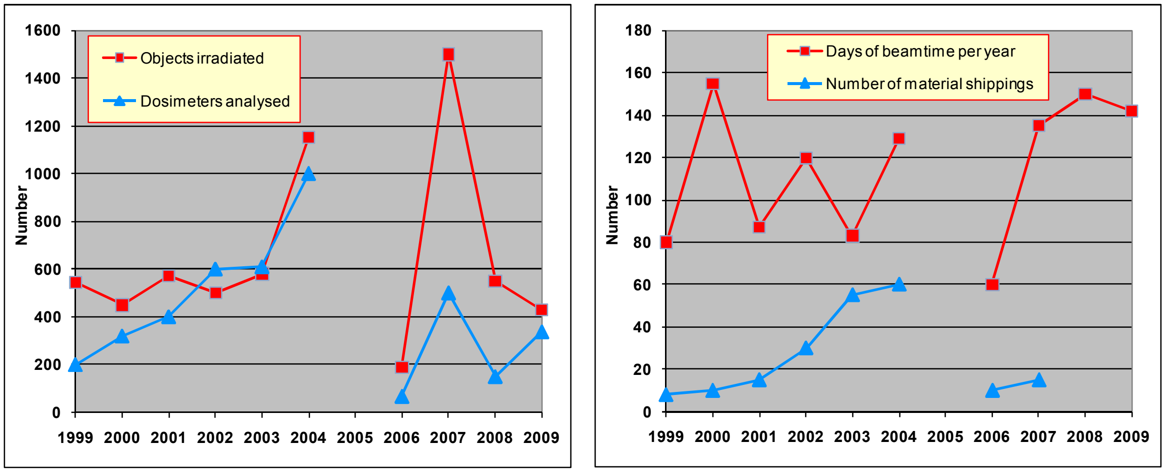


Figure 2: Number of irradiated samples and number of performed dosimeter measurements per indicated year (left). Number of days the proton facility was operated per year and number of (activated) material shipping's organized and handled through the Facility operators. In 2005 no beams were available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

3.2 CERF – CERN-EU High-Energy Reference Field

3.2.1 CERF – Facility layout and spectra

The CERF facility [6] (Figure 3) is installed in one of the secondary beam lines (H6) from the Super Proton Synchrotron (SPS) in the North Experimental Area.

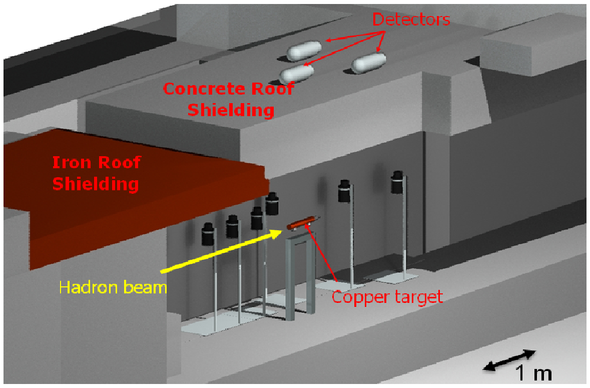


Figure 3: Layout of the CERF facility in the North Experimental Hall of the SPS as modeled in FLUKA. The side shielding is removed to show the inside of the irradiation cave with the copper target set-up

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 160cm respectively. On top of these 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 [7,8]. 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 energy 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.

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).

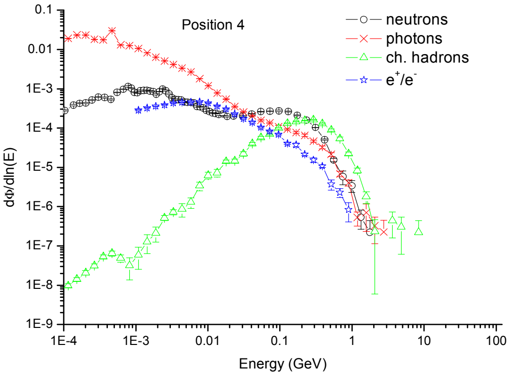


Figure 4: Typical particle fluence spectra obtained in reference position 4 lateral to the target.

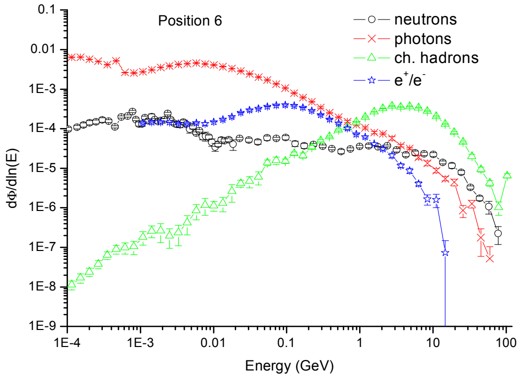


Figure 5: Typical particle fluence spectra obtained in reference position 6 downstream of the target.

3.2.2 CERF - Overview of experimental applications and recent experiments

3.3 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). CNGS radiation test areas

3.4 Other facilities and radiation test areas

Mention GIF++ and HIRADMAT for completeness

HIRADMAT [9] (reference, do not delete – cross-referenced later)

4 A survey on needs for irradiation facilities at CERN

The CERN Working Group for Future Irradiation Facilities [10] 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 6 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.

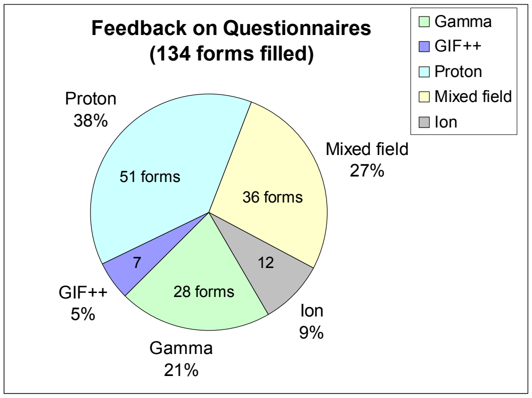


Figure 6: Distribution of answers received in the survey for the individual types of radiation facilities:

- **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, recent concerns for radiation damage in the LHC and its upgrade and/or accelerators in other HEP laboratories.
- **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 [11]. The third section reflects on recent requests that were not included in the 2008/2009 survey and finally the last section of this chapter gives the (preliminary) conclusions of the 'Radiation Facilities Working Group" based on the survey and the recent requests and developments.

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 [9], 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 7. 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.

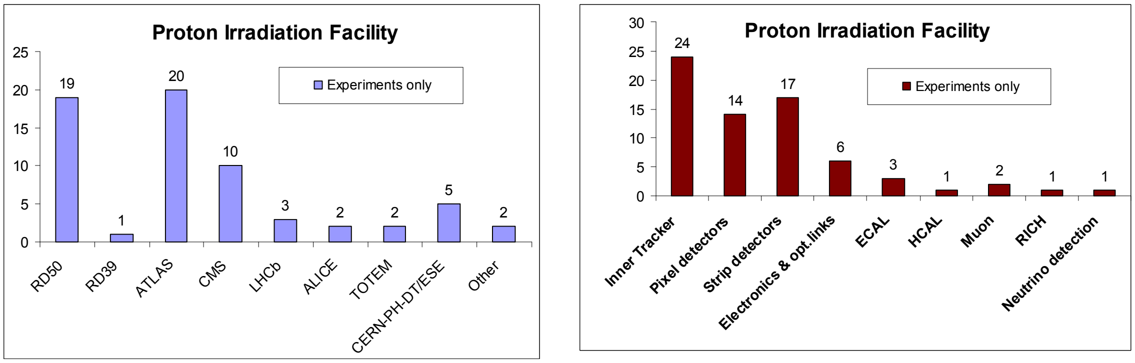


Figure 7: Questionnaires filled split up according to membership in collaborations and units of users (left) and according to detector types for which the person filling the questionnaire works. Double counting was used for persons working for several experiments or on several detector types.

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 [11]).

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 (please specify details below)	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 (please specify details below)	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 facility 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 form of a histogram in Figure 8. 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}.

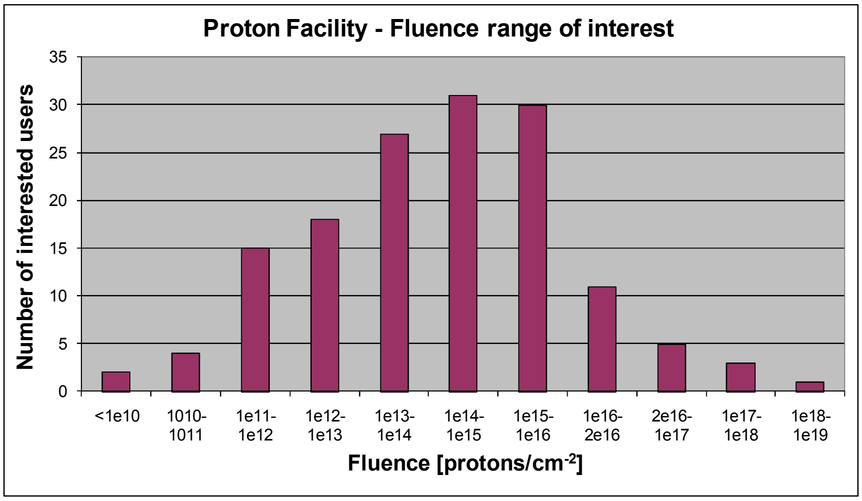


Figure 8: Number of users requesting to be able to perform irradiations in the indicated proton fluence range. The fluence is given in units of particles/cm^2 as requested by the users asking for homogeneous irradiations over their objects.

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 36 feedback forms were received. A splitting of form according to the user communities introduced previously is given in Figure 9 while Figure 10 indicates that feedback was obtained from CERN staff as well as CERN users. The majority of the answers (59%) 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.

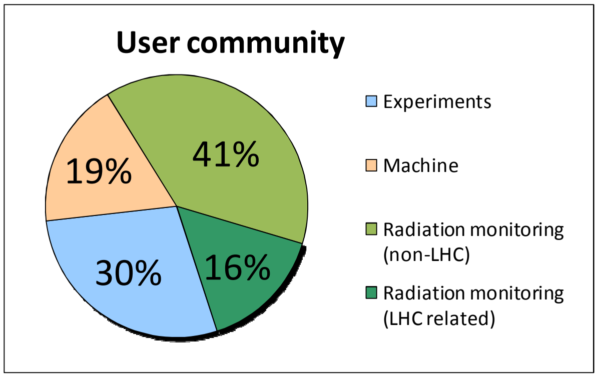


Figure 9: Splitting of the 36 forms according to user communities.

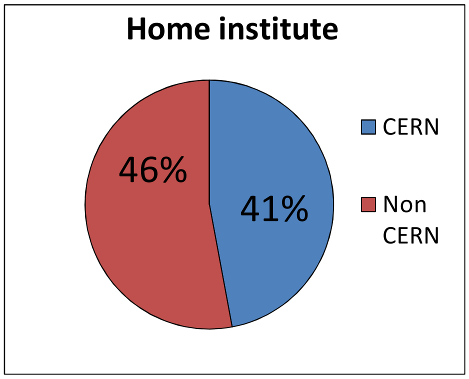


Figure 10. Splitting of answers according to home institute of users requesting the facility.

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 test

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 [11]).

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 (36 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. This last point is especially important for accelerator electronics which partly has to be tested in a full rack configuration (*e.g.*, power-converters).

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 field behind shielding is very similar for both energies except for the muon component directly downstream the target (see Appendices A.1 and A.2), 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.

Fast or slow extracted proton beam – Clear preference for slow extraction, fast extraction regarded as useful additional feature of a facility.
A clear preference was given to a slow extracted beam. 97% of the users would be using a slow extracted beam. However, 10% stated that they would require additionally a fast extracted beam and 40% stated that they would use a fast extracted beam if offered in addition to the slow extraction mode.

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.
A first 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). This estimate is based on extrapolations of calculations carried out for a conceptual design study of an irradiation facility named "CERF++" (see Appendix A.1). The results presented in Table 5 are given for a primary beam momentum of 24 GeV/c and an intensity of $1x10^{11}$ protons per 16.8 s. The dose and fluence values presented are based on one 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/n-fluence estimates as a function of the irradiation position around the target. This estimate is based on a 24 GeV/c proton beam impact on a 50 cm long copper target, a beam intensity of 1x10^{12} protons/16.8s and a continuous operation over one week resulting in a total beam intensity of 3.6x10^{16} protons/week is assumed.

	Size of homogenous irradiation area					
	2x2cm^2	2x2cm^2	2x2cm^2	10x10cm^2	25x25 cm^2	1x1m^2
Position	Target end position	Target side position	50 cm down-stream the target	20 cm lateral to the target	50 cm lateral to the target	150 cm lateral to the target
Dose (Gy/week)	5.04E+06	1.01E+06	2.52E+05	1.01E+05	2.02E+04	2.02E+03
n fluence (cm^{-2}/week)	3.60E+15	9.00E+15	1.80E+14	9.00E+14	1.80E+14	1.80E+13

Conclusion: Using a weekly beam intensity of 4x10^{16} protons at 24 GeV/c or 4x10^{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 three quarters of the users (for more details see [11]). For users aiming to irradiate with radiation levels corresponding to the innermost Pixel Layers of a luminosity upgraded LHC (approx. 2×10^{16} cm^{-2}), a 10 times higher intensity would be required.

4.3 Preliminary conclusions drawn from the survey

Rework the WG Memo from Lucie

4.4 Recent developments not included in the survey

Radiation effects in electronic devices can be divided 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:

1. radiation levels
2. inventory of installed electronics and failure consequences
3. expected radiation sensitivity
4. early monitoring and optimization possibilities
5. 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 11 and 12 show the respective radiation fields.

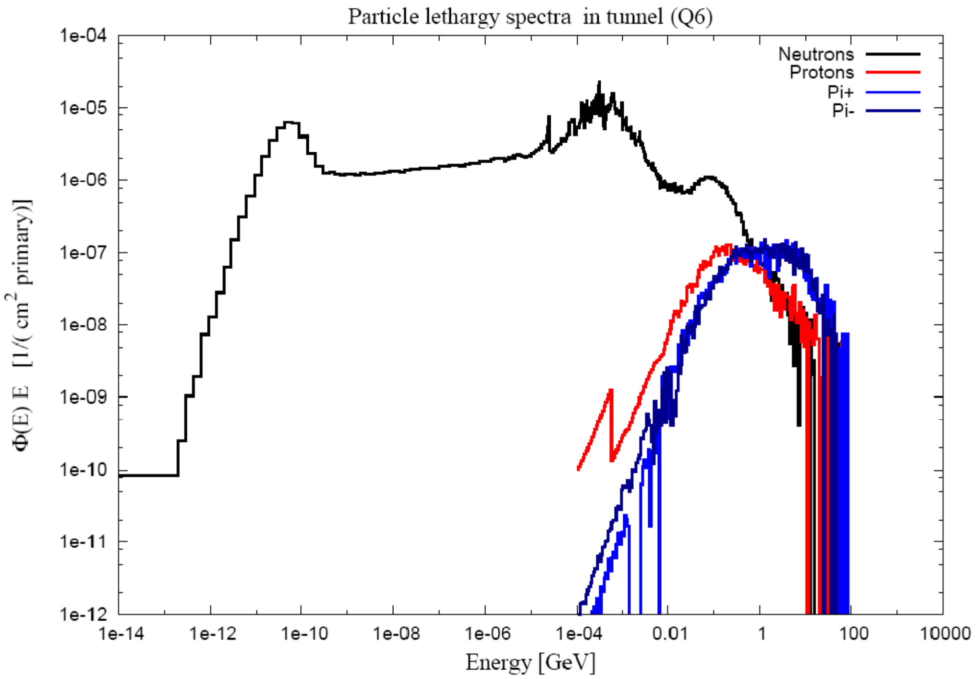


Figure 11: Particle energy spectra as seen by electronics installed in the LHC tunnel.

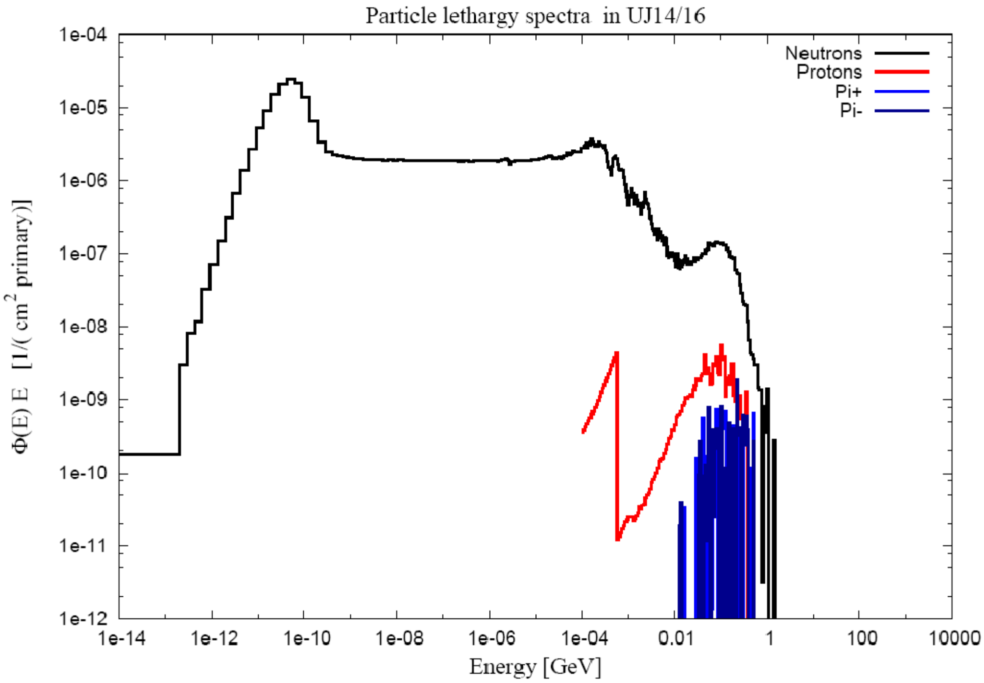


Figure 12: Particle energy spectra as seen by electronics installed in shielded LHC areas close to the tunnel.

Currently the CNRAD area (parasitic installation to CNGS operation) allows for radiation testing of electronics (see chapter 3.2), however with a certain number of shortcomings:

- radiation tests are performed parasitically to CNGS operation, thus strong access constraints exists (only few short accesses possible a year)

- equipment is manually placed within a radiation area (strict RP procedures apply)
- limited infra-structure is available (*e.g.*, not water cooling possible)
- radiation field is well characterized (given the size), but still significant uncertainties to be taken into account:
  - high radiation gradients
  - limited available space leads to 'packing equipment', thus altering the radiation field
  - radiation field analysis is based on Monte-Carlo calculations compared with installed monitoring with limitations in coverage and level of detail which can be included in the simulations (huge distances from the target to the actual radiation area)

In view of the years to come, these short-comings will strongly impact the flexibility and efficiency in the preparation of the mid/long-term mitigation actions for the LHC.

Input from Markus (where shall we put the spectra comparison between LHC and CNGS -> into the CNGS chapter I would suggest -> Michael, do you then compare it with the EastArea)?

5 Reflections on options for implementation and operation

…. Note that this is not part of request to LHCC (as implementation plans follow later) and in principle only the physics case should be judged. Howevre, since a lot of work has be done, it shall be given here as additional input. …

5.1 Radiation fields at the PS and SPS locations

…. Some input (to be shaped, give references to Appendices also):
Short discussion about fields arising from beam impacts on a target at 24 and 450 GeV/c

Except the positions located downstream of a cylindrical shaped Cu target (length: 50 cm, radius: 3.5cm) the shape of the particle spectra emerging from a proton beam impact at 24 and 450 GeV/c beam are similar. 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.

The differences of the radiation spectra seen downstream the target positions can be found mainly in the high-energy part of the cascade which is stronger pronounced in case of the 450 GeV/c beam impact. Another clear distinction between the two cases can be found downstream the target behind thick shielding (several meter of iron), where a strong muon domination can be found in case of the 450 GeV/c beam operation. This muon component can be seen as a well defined muon calibration field. On the other hand at high beam intensities it poses a radiation protection problem since it is almost impossible to entirely shield muons with an energy of up to 450 GeV (primary beam energy). Since the maximum energy of muons arising from a 24 GeV/c proton beam is *limited by the primary beam energy, the total absorption of muons emerging from this scenario is feasible by using approximately 17 m of iron.*

5.2 Estimate on available number of protons at PS and SPS locations

Give a strong argument for the combination of proton and mixed-field facilities

5.3 Potential locations and rough cost envelopes

Give a clear statement that this is work to be addressed to EN department.

6 Request to the LHCC

..... starting to draft:

- *Evaluate and comment on the long-term need of the LHC Experiments for proton and mixed-field radiation facilities at CERN in view of LHC operation and future luminosity upgrades.*
- *In view of the foreseen restructuring of the PS EAST HALL, give a statement on the long-term need for a combined proton and mixed-field facility based on a 24 GeV/c proton beam. If a combined facility at the PS should not be desirable, give a statement on alternative facilities.*
- *Give a recommendation in consensus with the LHC Experiments to study or not to study implementation and funding plans for an upgraded proton and/or mixed-field facility.*

Appendices

A. Operation of facilities at the PS or at the SPS?

A.1 Mixed radiation fields emerging from 450 GeV/c and 24 GeV/c protons

Based on a work by E.Feldbaumer and H.Vincke (CERN-DGS/RP)[12].

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 conceptual design study of an irradiation facility (see Figure 11 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 11 (right side).

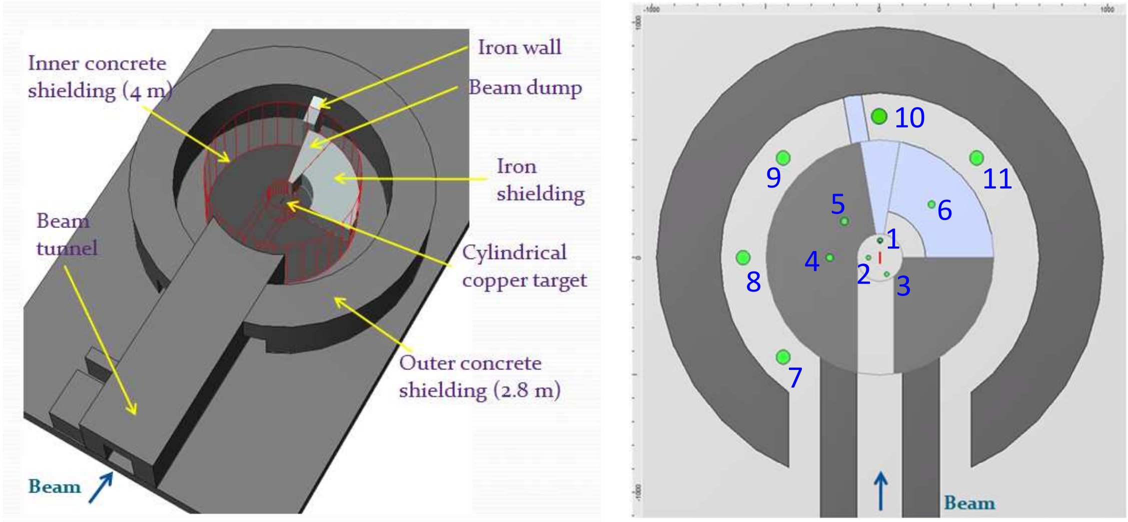


Figure 11: Conceptual design of the CERF++ irradiation facility (left site) and hypothetical measurement positions chosen for the radiation field comparison between 24 and 450 GeV/c proton irradiations. The right picture shows the locations (green circles) used for the comparison of the radiation fields.

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.

Results

Figure 12 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.

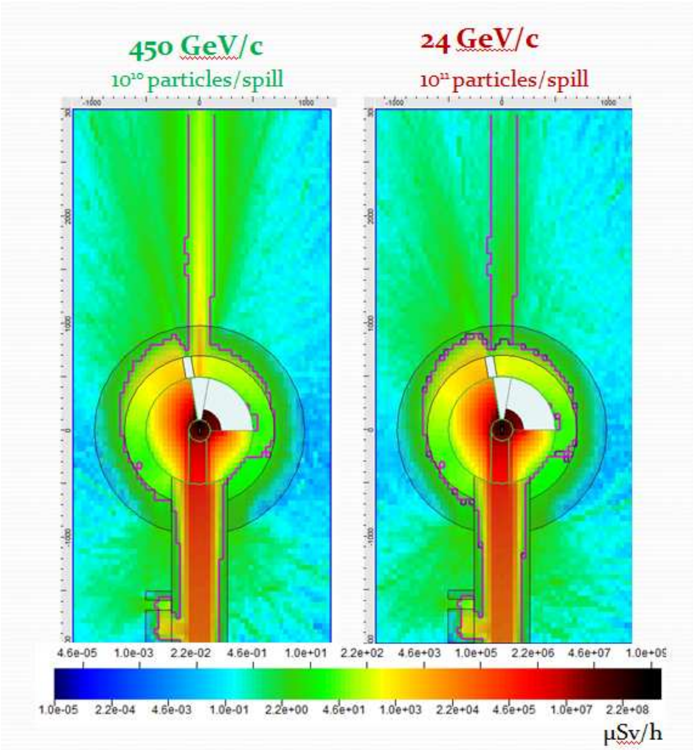
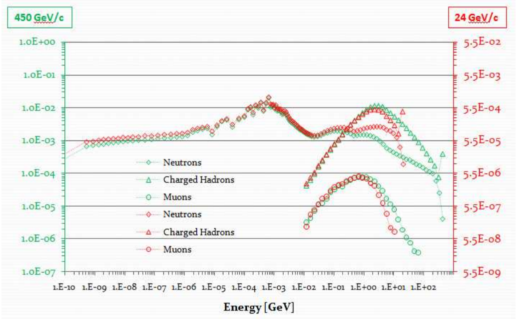


Figure 12: Cross section through the CERF++ area showing the dose rate at beam height. The purple contour line in the 450 GeV/c picture indicates the areas of a dose rate of 15 uSv/h. The blue line in the right picture serves the same purpose for the 24 GeV/c picture. To compare the two scenarios, the purple line is also displayed in the right plot.

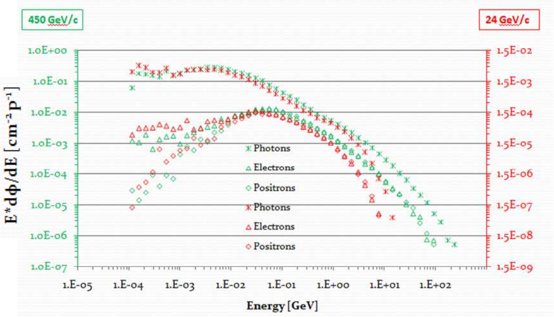
The comparison of the two color plots shows clearly that the dose rate conditions are very similar for both cases lateral and upstream the target position. In forward direction behind the iron dump a much higher dose rate can be found for the 450 GeV/c primary beam. The dominance of the 450 GeV/c scenario 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 12 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 13 presents the comparison of the fluence spectra at the measurement positions 1, 2, 8 and 10 (see Figure 11, right picture).

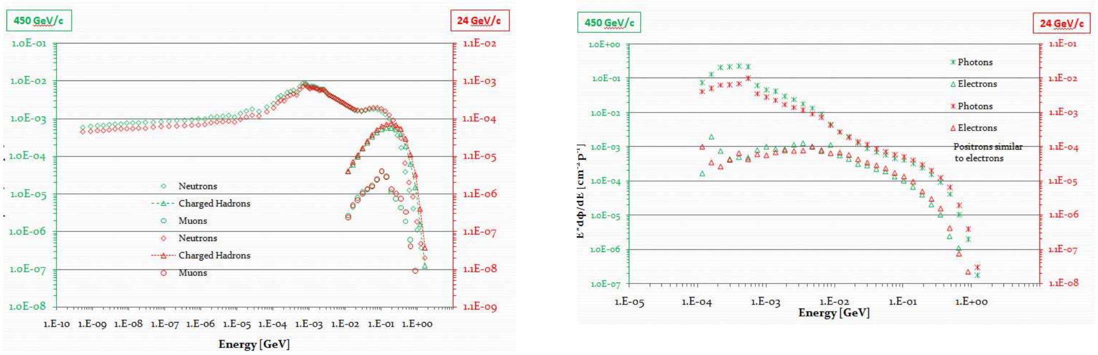
Inside downstream (Position 1)



Inside downstream (Position 1)



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



Outside downstream (Position 10)

Outside lateral (Position 8)

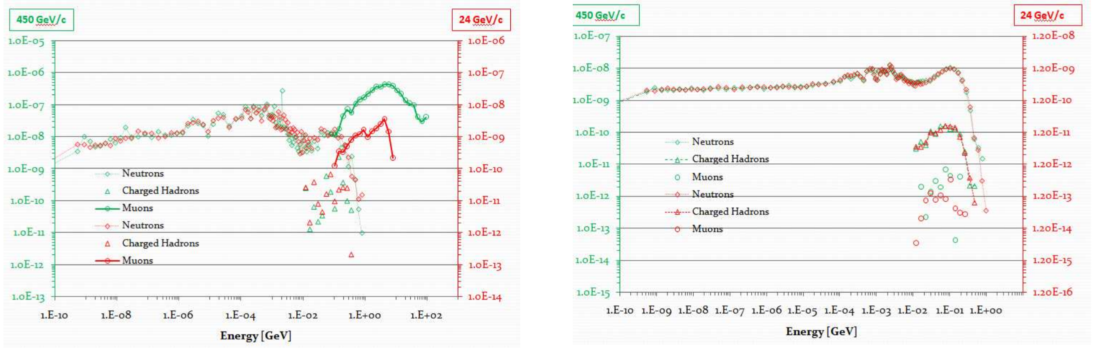


Figure 13: Comparison of the radiation fields seen at the measurement positions 1, 2, 8 and 10 emerging from the two different scenarios. The fluence scale, normalized to particles per primary proton, is displayed on the left side of the pictures for the 450 GeV/c case and on the right side for the 24 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 calibration field" cannot be produced by the 24 GeV/c irradiation setup. This well defined high-energy muon field can be seen as an advantage of the 450 GeV/c beam facility. However, one has also to consider the radiation protection difficulties to shield high-energy muon radiation.

A.2 Shielding considerations for mixed-field facilities at the PS or SPS

… include calculations from Helmut

B. Potential upgrade of the PS EAST HALL Facilities

.... Needs text ...

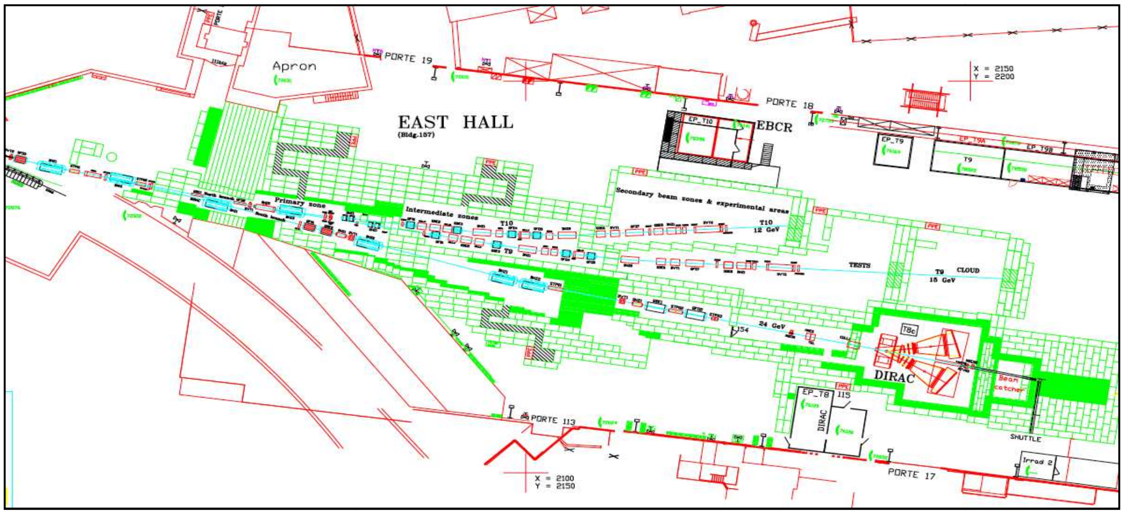


Figure 14: Proposal for a renovated East Area presented by L.Gatignon (CERN-EN) at the IEFC 2010 Workshop [1].

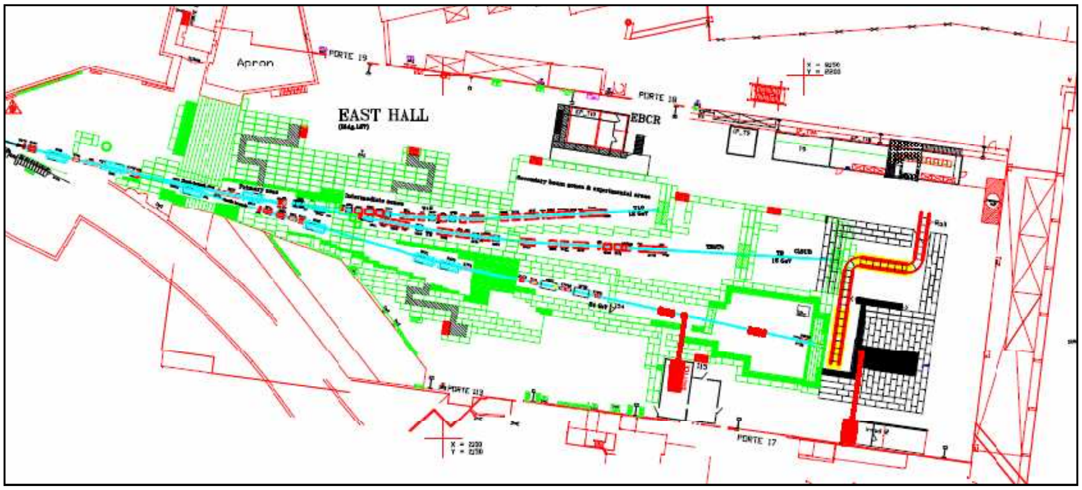


Figure 15: Principle of a combined proton and mixed-field facility sketched into the layout proposal given in Figure 14.

Some indications into figure where to find what; make clear this is a sketch not an implementation proposal

Acknowledgements

Whoever does not go into the authors list shall be acknowledged here (WG members)
Eduard Feldbaumer (BE/OP)

References

---

[1] Lau Gatignon, "East Area Renovation", IEFC Workshop 2010, http://indico.cern.ch/conferenceDisplay.py?confId=70866
[2] AIDA (Advanced European Infrastructures for Detectors at Accelerators), proposal submitted to FP7-INFRASTRUCTURES-2010-1 call from the European Commission, proposal approved, more details on https://espace.cern.ch/aida/default.aspx
[3] PS East Hall Irradiation facilities web page: http://irradiation.web.cern.ch/irradiation/
[4] M.Glaser et al., NIM A 426(1999).
[5] M.Glaser et al., IEEE TNS, Volume 53, Issue 4, 2006, 2016 – 2022.
[6] A. Mitaroff and M. Silari. The CERN-EU high-energy Reference Field (CERF) facility for dosimetry at commercial flight altitudes and in space. Radiation Protection Dosimetry 102, 7-22, 2002
[7] A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala, FLUKA: a Multi-Particle Transport Code, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.
[8] A. Fasso` et al., The Physics Models of FLUKA: Status and Recent Developments, Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), La Jolla, CA, USA, March 24-28, 2003, (paper MOMT005), eConf C0303241 (2003), arXiv:hep-ph/0306267.
[9] High-Radiation to Materials (HiRadMat) Facility of CERN/SPS: https://espace.cern.ch/hiradmat-sps/
[10] Working group on Future Irradiation Facilities at CERN: http://www.cern.ch/irradiation-facilities
[11] M.Moll and H.Vincke, "Survey on the demand, requirements and specifications for future High Energy Hadron Irradiation Facilities at CERN", to be published as PH Technical Note (draft version of document available on [10])
[12] E.Feldbaumer and H.Vincke, "Radiation field emerging from the impact of a 450 GeV/c and a 24 GeV/c proton beam", presented on 13.6.2008 on the "Irradiation Facilities Working Group" Meeting.