Radiation Protection at High Energy Accelerator Laboratories

D. Forkel-Wirth, S. Roesler, M. Silari, C. Theis, Heinz and Helmut Vincke
DG-SC

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Definition of Radiation Protection

**Radiation protection:** The protection of people from the effects of ionizing radiation, and the means for achieving this.

- Radiation Protection Training
- Assessment of radiological risks at work places
- Area monitoring
- Individual monitoring of personnel
- Control and characterization of radioactive material and waste
- Management of radioactive sources and waste
- Assessment of radiological risks related to new projects
- ...

Responsibility of **CERN’s Radiation Protection Unit**, providing expert advice, authorizing activities and controlling compliance of activities with RP rules.
Definition of Radiation Safety

**Radiation safety:** The achievement of proper operating conditions, preventions of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards.

- shielding
- beam operation
- access system
- fire prevention
- ventilation
- optimized design of facility
- ...

Responsibility of **the owner of the source** emitting ionizing radiation (CERN: Departments BE, PH, ENG, TE)
Ionising Radiation

Ionising radiation are

- photons (X-rays, γ-radiation)
- particles (α-, β- (e⁺, e⁻), p⁺, p⁻, n, π⁺, π⁻, μ⁺, μ⁻...)

transporting sufficient energy to ionise atoms and molecules

The interaction between ionising radiation and matter results in an energy absorption by and a subsequent potential radiation damage of matter.

Ionising radiation is part of the nature and of human activities in medicine, research, industry, energy production and military
Prompt Ionising Radiation

hadron accelerator

high energy, mixed radiation fields

beam on

up to 7 TeV

cosmos

up to $10^{10}$ TeV
Radiation Showers

Radiation showers development after impact of ONE hadron (120 GeV/c) on a copper target

Hadronic shower only

Hadronic shower + photons
Particle fields (SPS)

Attenuation of radiation $H_0$ (point source):

$$H = \frac{H_0 \times e^{-d/l}}{R^2}$$

$R$: distance
$l$: attenuation free path
concrete: $l = 40$ cm
iron: $l = 17$ cm
Ionising Radiation Due to Radioactivity

Radioactivity: the phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of ionising radiation. The rate at which this nuclear transformations occurs in matter containing radionuclides is called activity. The equation is

\[ A(t) = -dN/dt \text{ [Bq]} \]

where N is the number of nuclei of the radionuclide, and hence the rate of change of N with time is negative.

The radioactive half-life of a radionuclide is the time necessary for half of the nuclei present in the sample to decay

Radionuclides are either natural occurring or produced by nuclear reactions (artificial radionuclides).

\[ 1 \text{ Bq} = s^{-1} \]
Chart of Nuclei

unstable (=radioactive) nuclides

α-decay

β⁺: p⁺→n + e⁺

β⁻: n→ p⁺ + e⁻

α: AX → A-4Y + ⁴He²⁺
Radioactivity

$\beta^-, \gamma$-emitter:

pure $\beta$-emitter:

$\alpha$, $\beta$- and $\gamma$ are emitted with end energies up to few MeV
Terrestrial Radionuclides

During the creation of the earth, terrestrial nuclides had been incorporated into the earth crust ($T_{1/2}$ some millions of years)

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Half-life</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-235</td>
<td>$^{235}\text{U}$</td>
<td>$7.04 \times 10^8$ a</td>
<td>0.72% of natural Uranium</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$^{238}\text{U}$</td>
<td>$4.47 \times 10^9$ a</td>
<td>99.3% of natural Uranium</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>$^{232}\text{Th}$</td>
<td>$1.41 \times 10^{10}$ a</td>
<td></td>
</tr>
<tr>
<td>Potassium-40</td>
<td>$^{40}\text{K}$</td>
<td>$1.28 \times 10^9$ a</td>
<td>Earth: 0.037-1.1 Bq/g</td>
</tr>
</tbody>
</table>

...and some more:

$^{50}\text{V}, ^{87}\text{Rb}, ^{113}\text{Cd}, ^{115}\text{In}$, ... $^{190}\text{Pt}$, $^{192}\text{Pt}$, $^{209}\text{Bi}$, ...
Uranium-Radium Decay Chain

\[ T_{1/2} = 3.8 \text{ days} \]
Radon Map of Switzerland
Cosmogenic Radionuclides

Cosmogenic nuclides are produced by nuclear reaction of cosmic particles with stable nuclei of the atmosphere

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Half-life</th>
<th>Nuclear Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-14</td>
<td>$^{14}$C</td>
<td>5730 a</td>
<td>e.g. $^{14}$N(n,p)$^{14}$C;</td>
</tr>
<tr>
<td>Tritium-3</td>
<td>$^{3}$H</td>
<td>12.3 a</td>
<td>Interaction of cosmic radiation with N or O; $^{6}$Li(n,alpha)$^{3}$H</td>
</tr>
<tr>
<td>Beryllium-7</td>
<td>$^{7}$Be</td>
<td>53.28 d</td>
<td>Interaction of cosmic radiation with N or O</td>
</tr>
</tbody>
</table>

More cosmogenic radionuclides:
$^{10}$Be, $^{26}$Al, $^{36}$Cl, $^{80}$Kr, ...
...and we find radioactivity in our body

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Total activity in human body (~ 70 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>~ 1 Bq</td>
</tr>
<tr>
<td>Thorium</td>
<td>~ 0.1 Bq</td>
</tr>
<tr>
<td>Potassium 40</td>
<td>~ 4 - 5 kBq</td>
</tr>
<tr>
<td>Radium</td>
<td>~ 1 Bq</td>
</tr>
<tr>
<td>Carbon 14</td>
<td>~ 15 kBq</td>
</tr>
<tr>
<td>Tritium</td>
<td>~ 20 Bq</td>
</tr>
</tbody>
</table>
Artificial Radioactivity

Reaction Mechanism:

- *Fusion*
- *Fission*
- High Energy Nuclear Reaction (Spallation)
- more hadronic nuclear reactions \((p,n), (n,γ), \ldots\)
- *Gamma induced nuclear reaction* \((γ,n)\)
Fission

\[ ^{235}\text{U} + \text{n} \rightarrow ^{236}\text{U}^+ \]

Fission products

\[ ^{59}\text{Co} + \text{n} \rightarrow ^{60}\text{Co} \]

\[ ^{23}\text{Na} + \text{n} \rightarrow ^{24}\text{Na} \]
Spallation

$p$ + $^{56}\text{Fe}$ → stable $^{208}\text{Pb}$ + $^{49}\text{V}$

stable $^{208}\text{Pb}$ → $^{189}\text{Ir}$ + radioactive $^{49}\text{V}$

Secondary reactions
Production and Decay of Radionuclides

Rule-of-thumb (probably very obvious):

the shorter the half-life, the fastest the build-up, the fastest the decay

$$A = A_s \left(1 - e^{-t_{irr} / \tau}\right) e^{-t_{dec} / \tau}$$

It takes about 5 half-lives to reach saturation of activity
Activation of Material

Beam losses result in the activation of material (beam line components, tunnel structure, etc.)
Ambient Dose Equivalent Rate as Function of LHC Operation

M. Huhtinen, RPC/2003/XXXVIII/138
Activation of air, gas, water, cooling liquids,

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Halflife</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be-7</td>
<td>53 D</td>
</tr>
<tr>
<td>Na-22</td>
<td>3 Y</td>
</tr>
<tr>
<td>Sc-46</td>
<td>84 D</td>
</tr>
<tr>
<td>Cr-51</td>
<td>28 D</td>
</tr>
<tr>
<td>Mn-54</td>
<td>312 D</td>
</tr>
<tr>
<td>Co-56</td>
<td>77 D</td>
</tr>
<tr>
<td>Fe-59</td>
<td>45 D</td>
</tr>
<tr>
<td>Co-60</td>
<td>5 Y</td>
</tr>
<tr>
<td>Zn-65</td>
<td>244 D</td>
</tr>
</tbody>
</table>

ventilation filter (SPS)

γ-emitter only

demineralised water (SPS)

γ-emitter only
Radiological Quantities and Units

**Absorbed Dose** $D$:
- **Unit:** energy absorbed per mass
- $1 \text{ Gy} = 1 \text{ J/kg}$

\[ D_T = \frac{1}{m_T} \int D dm \]

**Equivalent Dose** $H$:
- absorbed dose of organs weighted by the radiation weighting factor $w_R$ of radiation $R$:
- **Unit:** $1 \text{ Sv} (= w_R \times \text{Gy})$

\[ H_T = w_R D_{T,R} \]

**Effective dose** $E$:
- Sum of all equivalent doses weighted with the weighting factor $w_T$ for tissue $T$
- **Unit:** $1 \text{Sv}$

\[ E = \sum_T w_T H_T \]
# Radiation Weighting Factors

<table>
<thead>
<tr>
<th>Type and energy of radiation $R$</th>
<th>Radiation weighting factor, $w_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons, all energies</td>
<td>1</td>
</tr>
<tr>
<td>Electrons and muons, all energies</td>
<td>1</td>
</tr>
<tr>
<td><strong>Neutrons:</strong></td>
<td></td>
</tr>
<tr>
<td>$&lt; 10$ keV</td>
<td>5</td>
</tr>
<tr>
<td>10 to 100 keV</td>
<td>10</td>
</tr>
<tr>
<td>$&gt; 0.1$ to 2 MeV</td>
<td>20</td>
</tr>
<tr>
<td>$&gt; 2$ to 20 MeV</td>
<td>10</td>
</tr>
<tr>
<td>$&gt; 20$ MeV</td>
<td>5</td>
</tr>
<tr>
<td>Protons, other than recoil protons, $E &gt; 2$ MeV</td>
<td>5</td>
</tr>
<tr>
<td><strong>ICRP 103 (protons and charged pions)</strong></td>
<td>(2)</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, heavy nuclei</td>
<td>20</td>
</tr>
</tbody>
</table>
Neutron Radiation Weighting Factors (ICRP 103)

Values for neutrons replaced by a continuous function in ICRP 2007
Biological Effects

**Stochastic effects:**
- no dose threshold (linear function of dose)
- increase of probability by 5% per Sv for:
  - genetic defects
  - cancer
- result does not depend on the amount of absorbed dose
- delayed health detriments

**Deterministic effects:**
- dose received in short time interval
  - dose threshold: > 500 mSv
- immediate consequences:
  - vomiting
  - immun deficiency
  - erythema and necrose
- health detriments are function of the dose
- lethal dose: 5 – 7 Sv
History of Radiation Protection

- Roentgen
  - 1880
  - 700 mSv
- M. Curie
  - 1890
  - 20 mSv
- ICRP
  - 1930
  - 20 mSv
  - 1940
  - 50 mSv
  - 1950
  - 50 mSv
  - 1960
  - 50 mSv
  - 1970
  - 50 mSv
  - 1980
  - 50 mSv
  - 1990
  - 50 mSv
  - 2000
  - 1 mSv
- Annual public limit
  - 1 mSv
- Annual occupational limit
  - 30 Sv

Source: Los Alamos Science Nr. 23, 1995, p. 116
General Principles of Radiation Protection Legislation

1) **Justification**
   
   any exposure of persons to ionizing radiation has to be justified

2) **Limitation**
   
   the personal doses have to be kept below the legal limits

3) **Optimization**
   
   the personal doses and collective doses have to be kept as low as reasonable achievable (ALARA)
Dose Limits

<table>
<thead>
<tr>
<th></th>
<th>Non-occupationally exposed persons</th>
<th>Occupationally exposed persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURATOM</td>
<td>&lt; 1</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>Germany</td>
<td>&lt; 1</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>CERN</td>
<td>&lt; 0.3</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>Switzerland</td>
<td>&lt; 1</td>
<td>&lt; 20</td>
</tr>
</tbody>
</table>

*Dose limits for 12 months consecutive (mSv)*
CERN’s Area Classification

<table>
<thead>
<tr>
<th>Radiation Area</th>
<th>Dose limit [year]</th>
<th>Ambient dose equivalent rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Work place</td>
<td>Low occupancy</td>
</tr>
<tr>
<td>Non-designated</td>
<td>1 mSv</td>
<td>0.5 μSv/h</td>
</tr>
<tr>
<td>Supervised</td>
<td>6 mSv</td>
<td>3 μSv/h</td>
</tr>
<tr>
<td>Simple</td>
<td>20 mSv</td>
<td>10 μSv/h</td>
</tr>
<tr>
<td>Limited Stay</td>
<td>20 mSv</td>
<td>2 mSv/h</td>
</tr>
<tr>
<td>High Radiation</td>
<td>20 mSv</td>
<td>100 mSv/h</td>
</tr>
<tr>
<td>Prohibited</td>
<td>20 mSv</td>
<td>&gt; 100 mSv/h</td>
</tr>
</tbody>
</table>

Signs:
- Radiation
- Limited Stay
- High Radiation
- Prohibited

Courtesy N. Conan, M. Widorski

Safety Instruction S3-GSI1, EDMS 810149
Optimization

• Any justified job is considered as optimized when different appropriate solutions have been evaluated and judged against each other from the radiation protection viewpoint,

• The decisional process leading to the chosen solution can be reconstructed at any time, and the risk of failure and the elimination of radioactive sources have been taken into account.

• Optimisation can be considered as respected if the activity never gives rise to an annual dose of more than 100 μSv for persons professionally exposed or 10 μSv for members of the public
Environment: The annual effective dose to the members of the reference group of the population (the most exposed group outside CERN) should stay below 10 uSv per year. The limit is 300 uSv per year.

Effective dose in uSv/year

<table>
<thead>
<tr>
<th>Year</th>
<th>From air/water releases</th>
<th>From stray radiation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>3</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>2004</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>2005</td>
<td>2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>2006</td>
<td>5</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>

Courtesy: P. Vojtyla SC-IE

Annual dose due to natural radiation in Geneva area: ~ 800 uSv per year
## CERN Reference Levels

**Occupationally exposed workers:** Annual individual, effective dose should stay below 6 mSv

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of persons with effective doses above 6 mSv/year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>13</td>
<td>Cable changes, maintenance of beam instrumentation, transport, radiation protection</td>
</tr>
<tr>
<td>2001</td>
<td>2</td>
<td>Transport, maintenance of beam instrumentation</td>
</tr>
<tr>
<td>2002</td>
<td>2</td>
<td>Transport</td>
</tr>
<tr>
<td>2003</td>
<td>5</td>
<td>Transport, radiation protection, Gamma radiography</td>
</tr>
<tr>
<td>2004</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
LHC Area Classification – Beam On

No access
(e.g., Machine, Experiments)

Supervised Areas:
(e.g., Counting rooms)
<table>
<thead>
<tr>
<th>Distance to beam line (without shielding)</th>
<th>Dose for full beam loss (Gy)</th>
<th>Dose rate at quench limit (Sv/h)</th>
<th>Dose rate caused by beam gas interactions (mSv/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ultimate</td>
</tr>
<tr>
<td>1 m</td>
<td>5500</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>2 m</td>
<td>2500</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>3 m</td>
<td>1200</td>
<td>3.3</td>
<td>7</td>
</tr>
<tr>
<td>5 m</td>
<td>500</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Quench limit: 1E7 protons/(m s)

Beam gas interactions (ultimate): ~1E16/year (200 days) ⇒ 21400/(m s)

Attenuation of concrete:
100 cm concrete ⇒ factor ~ 10
200 cm concrete ⇒ factor ~ 100
300 cm concrete ⇒ factor ~ 1000

Sv/Gy: approximated with 5

Remark: all dose and dose rates have to be doubled inside and increased by a factor of 20 % to 30 % outside due to photonic contribution.

Attenuation of concrete:
100 cm concrete ⇒ factor ~ 10
200 cm concrete ⇒ factor ~ 100
300 cm concrete ⇒ factor ~ 1000

Sv/Gy: approximated with 5
Design of ATLAS shielding

Effect of trigger holes is small (~15%). When these holes are filled their impact will be even smaller.

Dose rate varies in USA15 along the wall. Worst case are ~4 $\mu$Sv/h, and ~2 $\mu$Sv/h in the central region where the trigger cable ducts are located.

Courtesy: Ian Dawson
LHC Area Classification – Beam Off

Controlled Areas
(Collimation, Triplets, …)

Supervised Areas:
(Access galleries, …)

IR7 Stage 1
Arc: Loss of Single Bunch (2.82 x 10^9 protons)

Ambient dose equivalent rate

450 GeV

1 month cooling

7 TeV

<150 nSv/h (contact)

~1 μSv/h (contact)

Residual dose rates scale with beam energy approximately like \( E^{0.8} \)

\[(7000 \text{ GeV} / 450 \text{ GeV})^{0.8} = 9.0\]

\[(5000 \text{ GeV} / 450 \text{ GeV})^{0.8} = 6.8\]
Arc: Specific Activity after Single Bunch Loss

450 GeV

1 month cooling

7 TeV

2.8x10^9 p per bunch

factor 9

radioactive
Arc: Beam Gas Interaction (nominal)

Assumption: 2.4 \(10^4\) protons/m/s (both beams), 7TeV, lost for 180 days continuously (corresponds to an \(H_2\)-equivalent beam gas density of 4.5 \(10^{14}\) /m\(^3\))
LHC since 19th September 2008

Ambient dose equivalent rate is background with exception of
- TDI (Pt. 2 + 8)
- Collimators and absorbers (Pt. 3 + 7)

Survey collimateurs Point 3 LHC le 21/11/08

<table>
<thead>
<tr>
<th>N° CERCA</th>
<th>Mesures en μSv/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCS031</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCS014</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCS051</td>
<td>1.4</td>
</tr>
<tr>
<td>TCT023</td>
<td>5.2</td>
</tr>
<tr>
<td>TCT035</td>
<td>1.5</td>
</tr>
<tr>
<td>TCT047</td>
<td>0.1</td>
</tr>
<tr>
<td>TCSG 5R35</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCAPA 6R3 B2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCT074</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCT065</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCP 6L3 B1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCSG A5R3 B1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCSG B5R3 B1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>TCP 6R3 B2</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

Cooling liquids and gases not radioactive
Future Critical Regions of LHC

- Momentum and betatron cleaning regions at Points 3 and 7
- Beam dump caverns
- TCDQ/TCDS diluter system at Point 6
- TAS collimators in the ATLAS and CMS interfaces
- TAN neutral particle absorbers at Points 1 and 5
- Low-\(\beta\) regions at Points 1 and 5
- Dispersion suppressor regions at Points 1 and 5
Critical Regions

Regions of high losses (e.g., Collimators, …)

Regions with low losses (e.g., due to residual gas)

The LHC Loss Regions

Design criterion:

2 mSv per intervention and per person at work places with dose rates ranging from several 100 uSv/h to some mSv/h
How will it look like?

- Vacuum pump
- Quick-connect flanges
- Beam 2
- Collimator tank
- Interconnect support
- Collimator support
- Survey reference points
- Motorization/sensors

Narrow, thus difficult access

e.g. Exchange of motor on the tunnel side position in case of a tilted collimator
Detailed MC Calculations

- Remanent Dose Rates ranging from 0.1-20 mSv/h (cooling time of 8 hours to 4 months)

- Regular interventions

- Possible additional interventions on nearby elements (e.g., vacuum pumps, magnet modules, beam instrumentation)

- Possible failure of elements
# ALARA: Collimator Exchange LHC Point 7

<table>
<thead>
<tr>
<th>Actions</th>
<th>Collective Dose / mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1h</td>
</tr>
<tr>
<td><strong>without permanent bakeout</strong></td>
<td></td>
</tr>
<tr>
<td>CF with bolts</td>
<td>54.5</td>
</tr>
<tr>
<td>CF with chain clamps</td>
<td>51.4</td>
</tr>
<tr>
<td>CF with bolts + 2nd beam line</td>
<td>99.4</td>
</tr>
<tr>
<td>CF with chain clamps+ 2nd beam line</td>
<td>95.3</td>
</tr>
<tr>
<td><strong>with permanent bakeout</strong></td>
<td></td>
</tr>
<tr>
<td>CF with bolts</td>
<td>28.0</td>
</tr>
<tr>
<td>CF with chain clamps</td>
<td>24.9</td>
</tr>
<tr>
<td>CF with bolts + 2nd beam line</td>
<td>46.3</td>
</tr>
<tr>
<td>CF with chain clamps+ 2nd beam line</td>
<td>42.2</td>
</tr>
</tbody>
</table>
Dependency on Cobalt Content

Using a stainless steel type with low Co59 content will be important for the new n-TOF target design.

Materials have to be chosen according to the radiation fields they will be exposed to. N-TOF: dominated by thermal neutrons..... LHC: mainly dominated by high energetic hadron fields.
ALARA

Starts already during at the design phase:

• Choose the right material

• Design the components for optimised maintenance and repair (imagine yourself maintaining a radioactive component)

• Design the whole facility for optimised maintenance and repair (optimised lay-out, space, cranes, easy access to equipment, etc.)

Examples:

• Use of plug-in systems, e.g. for collimators allowing short installation and replacement times.

• Orientation of accelerator components in order to facilitate the access to the connection boxes at their less-radioactive end.
ALARA

Starts already during at the design phase:

Examples:

• Flanges for vacuum pipes which allow for easy coupling/de-coupling.

• Remote bake-out system for critical parts.

• Patch-panels for cables allowing an easier replacement and the use of especially radiation-resistant cables in high-loss areas.

• Use of cables with a radiation resistance of at least 500kGy.

• Placement of ionization chambers (PMI) to monitor remotely residual dose rates at locations with the highest expected losses.

• and....
And continues during the operation:

- Keep beam losses and such activation of components to the minimum – another person has to pay by taking a dose.
- Apply the ALARA principle for maintenance and repair – CERN's approach to ALARA needs to be respected.

The diagram shows the annual dose in mSv for the SPS. The x-axis represents the years from 1977 to 2008, and the y-axis represents the dose in mSv. The graph is color-coded, with blue representing shutdown dose and red representing the total dose. The data shows variations in dose levels across the years.
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