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Induced Activity Calculations in View of the Large Electron Positron Collider Decommissioning

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The future installation of the Large Hadron Collider (LHC) in the tunnel presently housing the Large Electron Positron collider (LEP) requires the dismantling of the latter after more than 10 years of operation. The decommissioning of an accelerator facility leads to the production of large amounts of waste, which in the case of an electron accelerator mostly is of very low level of radioactivity. LEP is classified as Nuclear Basic Installation (Installation Nucléaire de Base, INB) in France, where no unconditional clearance levels are fixed for the specific activity in materials to be released into the public domain. In the case of LEP, the possible sources of induced activity taken here into account are: localised beam losses, distributed beam losses and synchrotron radiation. Reference values of induced specific activity at saturation, normalised to lost beam power, were determined by comparing Monte-Carlo calculations carried out with the FLUKA code and experimental results. These figures are directly employed to estimate the expected amount of low level radioactivity around localised beam loss points in LEP. Regarding the synchrotron radiation, calculations of the total production of radionuclides from photon, thermal neutron and fast neutron activation in the aluminium vacuum chamber, the lead shielding and the magnet pole-faces of a dipole, showed that at beam energies less than 105 GeV, none of the components will be considered as radioactive for decay periods of longer then ten days.

KEYWORDS*: *Monte-Carlo calculations, induced radioactivity, low level radioactive waste, synchrotron radiation, electron accelerator, accelerator decommissioning, photonuclear reactions.

I. Introduction

The dismantling of the CERN Large Electron Positron collider (LEP) in view of the future installation of the Large Hadron Collider (LHC) calls for a thorough assessment of the expected amount of low level radioactive material which will be produced during the accelerator decommissioning. Although induced radioactivity in electron accelerators is far less important than in proton accelerators, in the present case the decommissioning procedure is complicated by the fact that LEP is classified as Nuclear Basic Installation (Installation Nucléaire de Base, INB) in France, where no unconditional clearance levels exist for specific activity in materials to be released into the public domain. Release of material may be allowed, if a detailed theoretical study is made supported by experimental measurements showing which parts of the machine could have (or not) been subjected to activation phenomena.

The aim of such a study is a "zoning" of the accelerator tunnel, i.e. a classification of areas where material may or may not have been activated. To demonstrate that most of the LEP components are “non radioactive”, one has to prove that beam losses around the ring (or any other mechanism) cannot give rise to values of specific activities that are above 1/10 of the exemption limits provided by the European Directive of 13 May 1996[(1)] in any given material. For most radionuclides found in accelerator components the exemption limit is 10 Bq/g (with the exception of tritium and ^{7}Be for which the values are 10^{6} Bq/g and 10^{3} Bq/g, respectively).

Of the possible mechanisms leading to induced radioactivity in LEP, this paper discusses in detail two, namely localised beam losses and synchrotron radiation. Values of induced specific activity in the various materials of the accelerator components were determined both by Monte-Carlo calculations performed with the FLUKA code[(2,3)] and by experimental measurements. Additional measurements were performed on samples taken from a dipole recently removed from LEP.

II. Sources of induced activity

Four main sources of activation can be identified in the LEP tunnel: localised beam losses, distributed beam losses, synchrotron radiation and high energy X-rays emitted by the superconducting RF cavities[(4)]. This last mechanism will not be considered in the following since the superconducting RF cavities will be stored for a future re-utilisation and not treated as a “waste”.

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Distributed beam losses are mainly caused by electrons and positrons emerging at small angles from interactions at the centre of the four experiments (Bhabha scattering) and lost in the beginning of the arcs at both sides of the four even LEP points. The analysis of the induced activity in the LEP components due to this source needs proper Monte-Carlo simulations and is currently under progress.

Localised beam losses are the predominant source in most parts of the accelerator ring: the induced radioactivity comes from direct interaction of the beam with the materials of the beam line. Any material such as a dump, a collimator or any other machine element which is likely to intercept a fraction of the beam, will be radioactive and must be considered as such at the time of LEP dismantling. It is of utmost importance to be able to predict the expected amount of specific activity in all other components such as vacuum chamber, magnets, lead shielding, *etc.* situated near this radiation source.

Synchrotron radiation produced inside the dipoles may become a source of induced activity with the increase of the LEP energy above 100 GeV[5]. At these electron beam energies, the spectrum of the synchrotron radiation extends above 8 MeV, the approximate threshold energy for photo-neutron production in almost all materials. This part of the spectrum can be described by a falling exponential with increasing photon energy. The steepness of this exponential scales inversely with the 3rd power of the primary electron energy. Thus the production of radioactivity is increased by several orders of magnitude by changing the primary electron energy from 86 GeV to 105 GeV.

III. Induced activity from localised beam losses

In 1997 and 1998 two separate experiments were carried out to assess the radioactivity induced in the most abundant LEP materials, namely aluminium (vacuum chambers, dipole excitation bars), copper (RF cavities, magnet coils, vacuum joints, collimators, *etc.*), lead (shielding around the vacuum chamber), stainless steel (vacuum chambers, vacuum valves, bellows, *etc.*) and iron-laminated concrete (dipoles)[6,7]. In both experiments the activation came from the secondary radiation generated when a high-energy beam of electrons or positrons is stopped in an aluminium dump. Samples of the five materials were irradiated on the electron and positron dumps for approximately 5 months, at about 20 cm from the beam axis, and activated by the stray radiation; the results were normalised to the beam power deposited in the dump. The experiment is presently being repeated and the results for the operation of LEP in 1999 will be available at the end of the year.

The experimental results obtained in 1997 and 1998 were compared with detailed Monte-Carlo simulations of the experimental set-up performed with the FLUKA code[8,9]. Two approaches were used: 1) direct scoring of the radionuclide yield by the RESNUCLE option of FLUKA and 2) scoring of photon track-length and folding with cross-section data. RESNUCLE is a new option in FLUKA that enables the user to score the residual nuclides from inelastic interactions directly. It has been found that all radionuclides with a half-life longer than 60 days, those of interest in the present work, are predicted by FLUKA to within a factor of 2 of the experimental value, and several of them with even a better accuracy. The experimental data and the Monte-Carlo results were used to calculate values of specific activity in the five materials for all radionuclides with half-life longer than 60 days[10]. In order to be on the safe side and in view of the stochastic uncertainties in the measurements, the most pessimistic conversion coefficients between induced radioactivity in Bq/g and beam losses, measured in watt, were set for the prediction of specific activities in LEP.

Conversion coefficients from unit lost beam power to induced specific activity at saturation are given for copper in **Table 1**. Similar data were determined for all other materials irradiated in the two experiments[10]. As stated above, these conversion coefficients were obtained by exposing the samples at about 20 cm from an aluminium beam dump. In case of another material acting as beam stopper, the values may be slightly different.

Table 1 Conversion coefficients from average beam power (watt) to induced specific radioactivity at saturation A_S (Bq/g) for radionuclides produced in copper. Part of the induced activity come from impurities.

Radio-nuclide	$T_{1/2}$	Possible production reactions	A_S at saturation (Bq/g per watt)
$^{3}H^{(\#)}$	12.3 y	spallation	$3.1\ 10^{-1}$
^{46}Sc	83.8 d	spallation	$3.5\ 10^{-2}$
^{54}Mn	312.2 d	spallation $^{55}Mn(\gamma,n)$	$6.8\ 10^{-1}$
^{56}Co	77.7 d	spallation $^{56}Fe(p,n)$	$4.9\ 10^{-1}$
^{57}Co	271.8 d	$^{63}Cu(\gamma,2p4n)$ $^{56}Fe(p,\gamma)$ $^{57}Fe(p,n)$ $^{59}Co(\gamma,2n)$	2.2
^{58}Co	70.9 d	$^{63}Cu(\gamma,2p3n)$ $^{57}Fe(p,\gamma)$ $^{59}Co(\gamma,n)$	3.1
^{60}Co	5.27 y	$^{63}Cu(\gamma,2pn)$ $^{65}Cu(\gamma,2p3n)$ $^{59}Co(n,\gamma)$	2.8
^{65}Zn	244 d	$^{64}Zn(n,\gamma)$ $^{66}Zn(\gamma,n)$ $^{65}Cu(\gamma,pn)$	$3.6\ 10^{-2}$

(#) values for ^{3}H are estimated from the data of ^{7}Be

These conversion coefficients were used to predict the specific activity induced in the LEP materials for a typical beam loss scenario. A value of 1 W of beam power, on average, on a component is a fairly representative figure and the results can easily be scaled to a different power loss. Assuming a "standard" LEP operating period of 6 months

followed by a 6 month shutdown period, after the last run of a 10-years operating time the induced specific activity in the materials situated close (20 cm) to the irradiated component are given in **Table 2**. These values were estimated using the well-known expression for the build-up of the radioactivity generated by several irradiations each one followed by decay and the conversion coefficients reported in ref. (10).

Table 2 Estimated induced specific radioactivity in LEP materials around a loss point (e.g., a collimator) for a typical scenario of 10 year operation (6-month run followed by 6-month decay period). Values of specific activity are in Bq/g per watt of beam power lost in the component. A/A_S is the fraction of saturation activity reached by a given radionuclide at the end of this period.

Radio-nuclide	A/A_S	Induced specific activity (Bq/g per watt)				
		Al	Cu	St.-steel	Iron-conc.	Pb
^{3}H	0.218	0.72	0.07	0.08	0.39	0.06
^{22}Na	0.496	1.09	–	0.05	0.15	–
^{46}Sc	0.816	–	0.03	0.32	0.11	–
^{54}Mn	0.600	0.19	0.41	6.2	3.7	–
^{56}Co	0.833	–	0.41	1.2	0.12	0.03
^{57}Co	0.614	–	1.35	5.1	0.001	–
^{58}Co	0.853	–	2.6	6.6	0.005	0.001
^{60}Co	0.378	–	0.87	0.20	–	–
^{65}Zn	0.627	–	0.02	–	0.002	–
^{85}Sr	0.874	–	–	0.26	–	–
^{88}Y	0.762	–	–	0.03	–	0.001
^{88}Zr	0.817	–	–	0.03	–	0.007
^{110}Ag	0.622	–	–	–	–	0.002
^{124}Sb	0.889	–	–	–	–	2.8
^{207}Bi	0.097	–	–	–	–	0.13

Tritium cannot be determined experimentally by γ-spectrometry and the prediction by Monte-Carlo calculations is not straightforward as discussed in ref. (9). The values of specific activity were thus estimated from the experimental data of ^{7}Be via the ratio of their inelastic cross-sections, which are a factor of 3 to 5 times higher for tritium depending on the material in which this radionuclide is formed.

IV. Induced activity from synchrotron radiation

The total production of radionuclides due to synchrotron radiation (from photon, thermal neutron and fast neutron activation) in the aluminium vacuum chamber, in the lead shielding and in the magnet pole-faces were calculated using FLUKA[5]. Energy deposition in and around a typical main-ring dipole (**Fig. 1**) was estimated over an electron energy range from 86 GeV to 120 GeV.

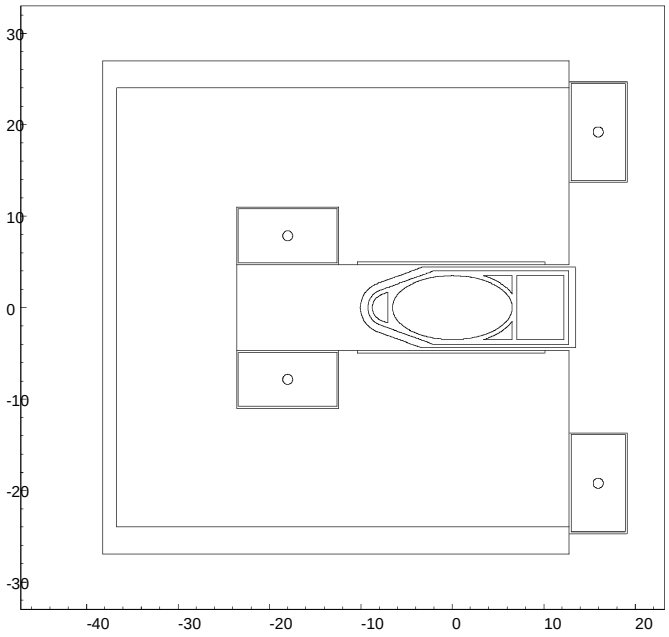

Fig. 1 Cross-section of a LEP dipole magnet and of the vacuum chamber as used in the Monte-Carlo simulations. Dimensions are in cm.

New methods have been developed for sampling photons from the steeply-falling energy spectrum of the synchrotron radiation so that these can be used as input of FLUKA. If one uses standard analogue techniques to sample photons, such as creating a cumulative distribution, the selected events would be dominated by photons at low energy, which neither deposit significant energy nor create any photo-hadron reactions. By selecting photon energies according to an exponential selection function, it is possible to parametrise the choice depending on whether one wants to give preference to high or low-energy selection.

Another aspect of the simulations that is important for the determination of the induced radioactivity in different materials is the evaluation of the activation cross-sections to be used. The number N of radionuclides produced by photons in a given volume can be calculated by the integral:

$$N = n \int_{E(thr)}^{\infty} \Lambda(E_\gamma)\sigma(E_\gamma)dE_\gamma$$

where n is the number of target nuclides per cm^3 in the volume, E(thr) is the threshold energy for that particular reaction, $\sigma(E_\gamma)$ is the photon-hadron cross-section at energy E_γ and $\Lambda(E_\gamma)$ is the differential photon track-length.

The track-length per unit energy falls by approximately one order of magnitude for each MeV increase in photon energy: due to this steep fall the integrand of the equation only contributes to the integral in the narrow energy range of the first few MeV above the threshold energy. It is therefore of major importance to have a good fit of the cross-section

data just above threshold. The photon-hadron cross-sections leading to radioactive isotopes were collected from the literature and evaluated for a synchrotron radiation spectrum. Only in a few cases the parameters of a Lorentz curve are known to fit the plot of the cross-section as a function of energy: in most of the cases a linear approximation (upper limit guess) for the cross-section above threshold was applied.

The results obtained by the track-length estimator were also compared with the results provided by the RESNUCLE option of FLUKA. The comparison is only possible for nuclides that have a high macroscopic cross-section (Al and Pb) and for regions where there is a high photon track-length (i.e. in the "nose" of the beam-pipe). The results are shown in **Table 3**.

Table 3 Comparison of the results from folding photon track-lengths with cross-section with the predictions of the RESNUCLE option for photon-induced radioactivity at electron energy E_e=100 GeV. The nuclide yield numbers are given per primary electron per metre of bend. The region considered is the nose of the beam-pipe.

Nuclide	RESNUCLE yield	Reaction	Track-length
^{26}Al	$1.84\ 10^{-13}$	^{27}Al(γ,n)^{26}Al	$3.16\ 10^{-13}$
^{205}Pb	$0.57\ 10^{-12}$	^{206}Pb(γ,n)^{205}Pb	$1.35\ 10^{-12}$
		^{207}Pb(γ,2n)^{205}Pb	$1.54\ 10^{-17}$
		^{208}Pb(γ,3n)^{205}Pb	$1.00\ 10^{-23}$

The photo-neutron reactions with materials of the beam-pipe are sources of neutrons. The activation due to thermal neutrons is produced by the (n,γ) reactions, for which, in general, the cross-section follows the 1/velocity law. The activation due to fast neutrons is not expected to give a large contribution in comparison to thermal neutron activation, therefore only an upper limit of the activation was estimated in ref. (5). The neutron production in three principal source regions was accounted for: the aluminium of the vacuum chamber via the Al(γ,n) reaction, the water cooling channels via the D(γ,n) reaction and the lead shielding via the Pb(γ,n) reaction. As can be seen from **Fig. 2**, below 100 GeV the deuterium in the water is the main source while above 100 GeV the contribution from lead dominates.

The total radioactivity in several regions of the LEP dipoles produced by the synchrotron radiation for energy E_e=100 GeV is shown as an example in **Table 4**. The total activities given in the tables are mainly due to impurities in the material, e.g. antimony in lead. The aluminium data also contain the contribution from the solder used to couple the aluminium of the vacuum chamber to the lead shield.

V. Experimental

A dipole was removed from LEP at the end of the 1998 operation at 94.5 GeV, to leave room for a spectrometer magnet for beam energy calibration.

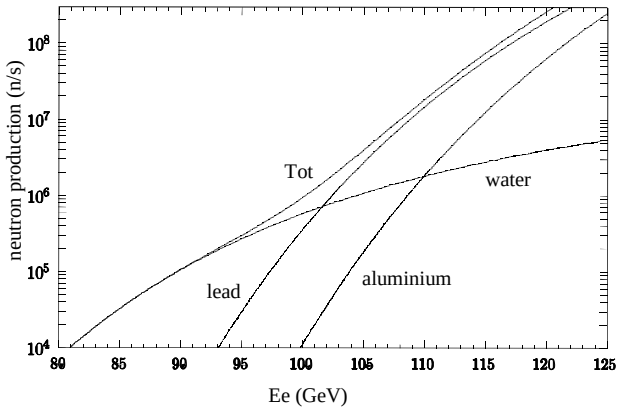

Fig. 2 Neutron production contributions from the aluminium, water and lead of the beam pipe as a function of primary electron energy E_e per metre of bend at a current of 5 mA.

Table 4 Total specific activity in several regions of the LEP dipoles due to synchrotron radiation (Bq/g), for operation of LEP at E_e=100 GeV.

Decay times in days	Al (vacuum pipe)	Pb (shield)	Iron-concrete (pole-faces)
0	$3.38\ 10^{-1}$	$6.41\ 10^{-1}$	$3.56\ 10^{-2}$
1	$1.29\ 10^{-1}$	$4.53\ 10^{-1}$	$5.14\ 10^{-3}$
7	$3.64\ 10^{-2}$	$7.43\ 10^{-2}$	$3.75\ 10^{-3}$
30	$3.44\ 10^{-2}$	$4.36\ 10^{-3}$	$3.52\ 10^{-3}$
365	$1.76\ 10^{-2}$	$5.17\ 10^{-4}$	$1.96\ 10^{-3}$
3650	$4.30\ 10^{-4}$	$4.77\ 10^{-7}$	$9.96\ 10^{-5}$

The dipole, which had been in LEP since 1989, was installed in a high dispersion region of the accelerator, where the beam size is largest and the probability that the beam halo grazes the vacuum chamber is also greatest. Several samples were taken from the dipole to be analysed by γ–spectrometry and look for traces of induced radioactivity produced by either particle losses or synchrotron radiation. Samples of the aluminium of the vacuum chamber, of the lead shield, of the aluminium of the excitation bars and of the iron-laminated concrete of the magnet yoke and pole-faces were collected in several positions along the dipole. Particular care was exercised to sample separately the outer extremity of the vacuum chamber (the "nose") and the surrounding lead shielding (**Fig. 1**), in order to isolate possible traces of radioactivity induced by synchrotron radiation. The preliminary results, given in **Table 5**, show no signs of artificial radionuclides, in line with the Monte-Carlo predictions at 95 GeV[5].

VI. Conclusions

The experimental results and the comparison with the calculations for induced activity from localised beam losses showed that, under the assumption of a “standard” LEP operating period of 6 months followed by a 6 months shutdown period and after 10-years operating time, the

Table 5 Results of the γ–spectrometry measurements of the samples taken from the dipole.

Sample	Radionuclides	Specific activity (Bq/g)
Magnet yoke (iron-concrete)	^{40}K ^{226}Ra ^{232}Th	$9.1\ 10^{-2}$ $7.8\ 10^{-3}$ $8.8\ 10^{-4}$
Vacuum chamber (aluminium)	Natural radionuclides	Traces ($<10^{-3}$)
Shielding (lead)	Natural radionuclides	Traces ($<10^{-3}$)
Excitation bars (aluminium)	Natural radionuclides	Traces ($<10^{-3}$)

specific activity induced in the materials situated close (20 cm) to a beam loss point (for instance, a collimator) remains, for most radioisotopes, well below 1 Bq/g. A few radioisotopes (e.g., ^{57}Co, ^{58}Co in copper and stainless steel and ^{54}Mn in stainless steel and iron-concrete) exceed this limit; however, at 1 m distance from the source the activating field will be approximately 20 time weaker due to the inverse square distance law. Subsequently, the values of induced activity are lower by the same factor. Therefore it will be largely conservative to consider as low level radioactive material the components situated upstream and downstream of the beam loss point up to a distance of 1 m, all the rest being non radioactive.

Regarding the induced activity by photons from synchrotron radiation, the production of nuclei per electron and per metre of the dipole structure, and the activity in Bq per metre for beams of electron and positrons with a total current of 5 mA during an operating period of 1500 hours (typical annual LEP operation) was assessed. Using as a guideline that a component should be considered as radioactive if its specific activity is greater than 1 Bq/g, it has been shown that at beam energies of up to 105 GeV none of the components could be considered as radioactive for decay periods of longer than 10 days[(5)].

In the same operational hypothesis of 5 mA total beam current during an operational period of 1500 hours, the activation due to either thermal or fast neutrons[(5)] will also not lead to any significant induced activity.

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