Induced radioactivity in the vacuum chamber

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In this note, I estimate the levels of the radioactivity induced in the LHC-b vertex chamber. Interactions induced by neutrons are the main contributors to this effect. A comparison is made between the effects in chambers made of steel and of aluminium.

1 Introduction

The luminosity of the LHC is so high that induced radioactivity is going to be a major concern in some of the experiments. For example, the forward calorimeters of the collider experiments CMS and ATLAS will represent a serious health hazard after several years of operation and the LHC will produce more radioactive waste than all previous CERN accelerators and storage rings combined. In this note, we investigate the sources of induced radioactivity in the LHC-b vertex chamber and estimate the levels that may be expected. Fortunately, the luminosity in LHC-b is two orders of magnitude smaller than that in the mentioned collider experiments. Also, the vertex chamber is located far from the place where the beam particles deposit the bulk of their energy. Yet, induced radioactivity in the vertex chamber is by no means negligible.

2 Sources of induced radioactivity

As is typical for particle physics experiments carried out in a high-energy collider environment, most of the radioactivity that may be expected in the vertex chamber is the result of nuclear reactions induced by *neutrons*. The dominance of neutrons in this respect is caused by the following factors:

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1. In the absorption of the beam particles and the particles produced in the interactions upstream of the absorbers (calorimeters), huge numbers of neutrons are produced. The main production processes are the nuclear reactions in the hadronic absorption. It has been measured [1] that in the absorption of hadrons in lead, about 20 neutrons/GeV are produced. Most of these neutrons are the result of nuclear evaporation, their typical spectrum peaks at a few MeV. In lead, such evaporation neutrons outnumber protons by an order of magnitude, in low-Z absorber materials, the difference is smaller but still very substantial.

2. Neutrons do not lose energy by ionizing the material they traverse. They are not subject to the electromagnetic force and only lose energy through processes involving the strong nuclear force. As a result, a significant fraction of the neutrons produced in the absorption processes mentioned above typically escape the absorber. On the other hand, soft protons produced in the absorption process lose their energy close to the point of production and rarely escape the absorber.

3. Since neutrons are electrically neutral, they do not have to overcome the (repulsive) coulomb barrier felt by protons in order to induce a nuclear interaction.

The neutrons that escape from the absorber material in which they are produced behave like a gas. They quickly spread throughout the entire experimental area, bouncing off the walls as a result of elastic collisions with atomic nuclei, in which process usually very little energy is transferred. They continue to move around in the experimental area until one of two things happens:

- They induce a nuclear transformation in which they are absorbed in an atomic nucleus.

- They decay: $n \rightarrow p + e^{-} + \bar{\nu_e}$

Since the half-life of the latter process is long (14 minutes), nuclear reactions are more likely to occur. The simplest and most frequent process for the low-energy neutrons considered here is *nuclear capture*, but (n, p) and (n, α) reactions are also quite common. If the atomic nucleus transformed in such processes is unstable, induced radioactivity is the result.

Not all induced radioactivity represents a problem. If the unstable nuclides produced in these processes have half-lifes less than 1 hour, exposure to radiation

can simply be avoided by waiting one day before entering the experimental area after the end of a beam exposure. Nuclides with very long half-lives (*e.g.* , > 1000 years) are usually also no problem, since the production of such nuclides in beam exposures, which last typically less than one year, is such that the decay rates are very small. If the unstable nuclides decay predominantly by emitting α or β particles (and no energetic γ's), exposure to radiation can be avoided with very simple means, *e.g.* a sheet of plastic.

In practice, the most problematic nuclides are γ emitters with a half-life between 1 month and 10 years, and especially those which have a large branching ratio for γ's with energies in excess of 1 MeV. Such γ's are very penetrating and require substantial shielding.

The following Table contains a list of nuclides that fall into this category, and which may be produced by neutron induced nuclear reactions in stainless steel.

Table 1: Characteristics of nuclides that may be produced in neutron-induced nuclear interactions in a vertex chamber made of stainless steel.

Nuclide	**Half-life**	**Gammas, keV (b.r.)**	**Production**
^{22}Na	2.6 yr	511 (2), 1275 (1)	Spallation
^{46}Sc	85 d	889 (1), 1120 (1)	Spallation
^{48}V	16 d	511 (2), 990 (1), 1330 (1)	Spallation
^{51}Cr	28 d	320 (0.08)	$^{50}\mathrm{Cr}(n,\gamma)$, $^{54}\mathrm{Fe}(n,\alpha)$
^{54}Mn	300 d	835 (1)	$^{54}\mathrm{Fe}(n,p)$, $^{56}\mathrm{Fe}(n,t)$
^{59}Fe	45 d	1099 (0.57), 1291 (0.43)	$^{58}\mathrm{Fe}(n,\gamma)$
^{56}Co	77 d	511 (2), 846 (1), 1238 (.66)	$^{58}\mathrm{Ni}(n,t)$
^{57}Co	270 d	122 (0.85), 136 (0.06)	$^{58}\mathrm{Ni}(n,pn)$
^{58}Co	72 d	511 (0.3), 811 (1)	$^{58}\mathrm{Ni}(n,p)$
^{60}Co	5.3 yr	1173 (1), 1332 (1)	$^{60}\mathrm{Ni}(n,p)$, $^{59}\mathrm{Co}(n,\gamma)$

For each nuclide, the half-life and the energy and branching ratio of characteristic γ rays are listed, as well as the reaction(s) that may lead to its production. Many of these reactions involve nuclei of elements such as nickel or chromium, which are added to iron in the steel production process. Their content depends on the type of steel, which is therefore an important ingredient for the calculations.

One of the most problematic nuclides is ^{60}Co, which is easily produced by neutron capture in ^{59}Co, the natural form of cobalt. As a result, cobalt-steel is very prone to activation in a neutron environment.

The calculations described in the following section have been carried out for the steel type known as 316L, which contains, besides 70% iron, admixtures of 17% chromium, 11% nickel, 2% molybdenum and traces of carbon and cobalt. Also most aluminium used for machining structures such as the LHC-b vertex chamber contains admixtures. The calculations have been performed for the material AMP 8000, which contains 6.7% zinc, 2.6% copper and 2.6% magnesium as the most important admixtures.

3 Description of the calculations

As a starting point of the calculations, I used the particle fluxes in the vertex detector area calculated by V. Talanov [2]. Figure 1 shows an example of these fluxes, at vertex station #6.

This figure shows that practically all charged particles originated from the pp interaction vertex, while most of the neutrons, especially those at distances of more than a few cm from the beam line did *not* originate from the pp interaction vertex. The figure shows that the flux of neutrons from sources other than the interaction vertex is independent of the distance r from the beam line (for $r > 3$ cm), contrary to all other particles, for which the flux strongly decreases as a function of r.

The fluxes shown in Figure 1 are normalized per interaction. Assuming a luminosity of $2 \cdot 10^{32}$ cm^{-2} s^{-1} and a total cross section of 100 mb, the number of interactions is estimated at $2 \cdot 10^{7}$ per second, or $2 \cdot 10^{14}$ per year. At these rates, the neutron flux for $r > 3$ cm is expected to be $2 \cdot 10^{12}$ cm^{-2} yr^{-1}.

Next, we need the interaction probability for a given neutron when it traverses the vertex chamber material. This interaction probability depends, among other things, on the neutron energy and on the thickness of the traversed material. As an example, we consider the production of ^{54}Mn, through the reaction ^{54}Fe (n, p) ^{54}Mn. The cross section for this process is ~ 0.1 b at 2 MeV and rises to ~ 0.5 b for 10 MeV neutrons. Given the production spectrum of the neutrons, 0.1 b is probably a realistic effective cross section. The production of ^{54}Mn in 316L steel can then be estimated as follows.

The mean free path ($\langle l \rangle = A/(\sigma N_A)$, with A being the atomic number, σ the cross section and N_A Avogadro's number) of a few-MeV neutron in a plate made

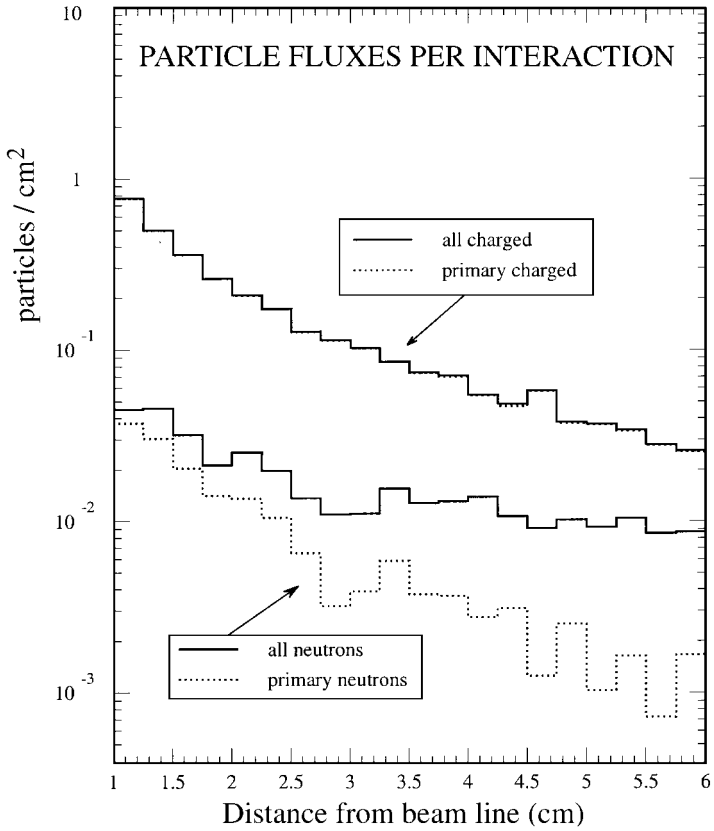

Figure 1: The total charged hadron and neutron fluxes (solid histograms) and the fluxes of charged hadrons and neutrons originating from the pp interaction vertex (dotted histograms) at vertex station #6, as a function of the distance from the beam line. The particle fluxes are normalized to one pp interaction.

of ^{54}Fe is equal to $54/(6.02 \cdot 10^{23} 10^{-25}) \approx 900$ g cm^{-2}. Therefore, the interaction probability of a neutron in such a plate is about 0.9% per cm (7.9 g cm^{-2}).

The production of ^{54}Mn in one kg of this steel is then found as the product of the neutron flux ($2 \cdot 10^{12}$ n cm^{-2} yr^{-1}), the surface of 1 kg of steel with a thickness of 1 cm (127 cm^2), the interaction probability of a neutron traversing this layer (0.9%, see above) and the fraction of ^{54}Fe target neuclei in this material (4.2%, since 70% is iron and the abundance of ^{54}Fe in natural iron is 6%). This gives a yield of $\sim 10^{11}$ ^{54}Mn nuclei per kg of steel and per year. Taking into account the effects of decay and the fact that a typical LHC run will last 200 days, we estimate the ^{54}Mn concentration at the end of the first run at $N_0 = 5 \cdot 10^{10}$ nuclei/kg. Given

the decay constant of ^{54}Mn ($\lambda = \ln 2/T_{1/2} = 2.8 \cdot 10^{-8}\mathrm{s}^{-1}$), the specific activity of ^{54}Mn, $dN/dt = \lambda N_0$, may thus be estimated at 1.4 kBq/kg.

Table 2: Neutron induced nuclear reactions that may activate a vertex chamber made of stainless steel, and their thresholds.

Thresholds for neutron reactions	
Reaction	**Q (MeV)**
^{50}Cr (n,γ) ^{51}Cr	9.3
^{58}Fe (n,γ) ^{59}Fe	6.6
^{59}Co (n,γ) ^{60}Co	7.5
^{54}Fe (n,p) ^{54}Mn	0.1
^{58}Ni (n,p) ^{58}Co	0.4
^{60}Ni (n,p) ^{60}Co	–2.0
^{58}Ni (n,pn) ^{57}Co	–8.2
^{58}Ni (n,t) ^{56}Co	–11.1
^{62}Ni (n,t) ^{60}Co	–12.0
^{56}Fe (n,t) ^{54}Mn	–11.9
^{54}Fe (n,α) ^{51}Cr	0.8

We have performed similar calculations for other nuclides that may contribute to the induced radioactivity of a steel vertex chamber. Because of the characteristics of the neutron spectrum, we ignored processes with Q-values below -5 MeV (see Table 2). This leaves only a small number of processes contributing at a significant level to the (long-term) induced radioactivity of a steel vertex chamber. These processes, the half-life of the resulting nuclide and their contribution to the specific radioactivity at the end of the first 200 days of running are:

^{58}Ni (n,p) ^{58}Co	$T_{1/2} = 72$ d	5 kBq/kg
^{60}Ni (n,p) ^{60}Co	$T_{1/2} = 5.3$ yr	0.5 kBq/kg
^{58}Fe (n,γ) ^{59}Fe	$T_{1/2} = 45$ d	3 kBq/kg

It is interesting to note that none of the mentioned target nuclei is very abundant in steel. The most abundant one is ^{58}Ni, which occurs for $\sim 7\%$. The abundance of ^{58}Fe is only 0.2%, but owing to the large capture cross section, the production of ^{59}Fe contributes yet significantly to the induced radioactivity.

This example illustrates that the large cross section for capture reactions may make even trace elements very important. The most important one of these trace elements is of course cobalt. Our calculations show that every percent of cobalt contributes 1 kBq/kg to the induced radioactivity of the steel chamber for a 200 day run. Because of the long half-life (5.3 yr), this cobalt accumulates over the years and may well dominate after a few years of operation.

The other mentioned capture reaction, in which ^{51}Cr is produced, is less important mainly because of its short half-life (28 days), and the small branching ratio for γ production (8%). Also, the γ rays emitted by this nuclide are much softer than for the other nuclides discussed here (320 keV) and therefore, self-absorption plays a larger role.

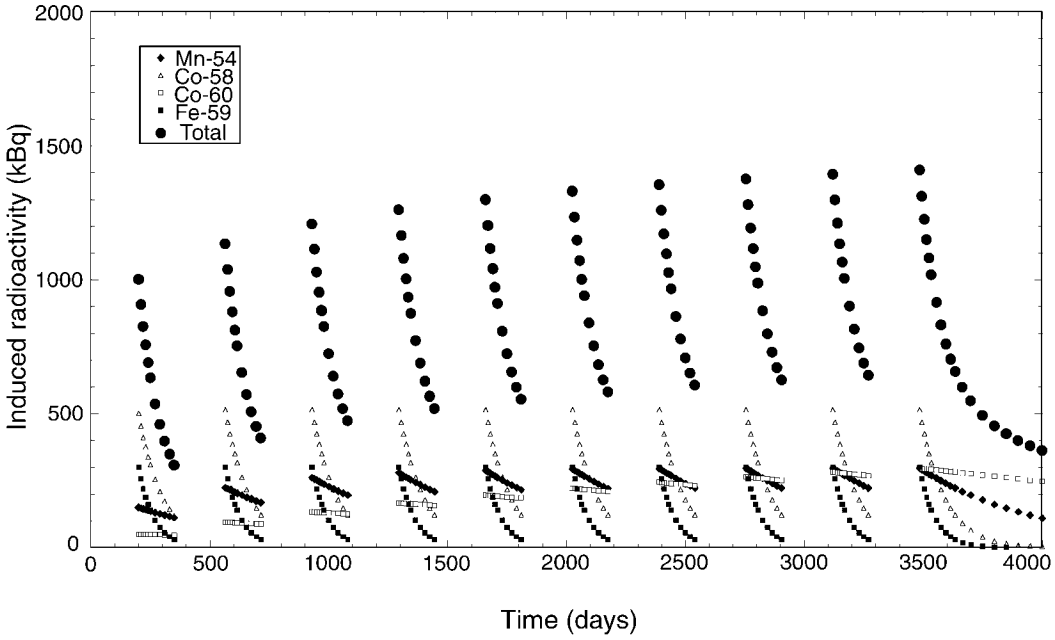

Figure 2: The specific radioactivity of a vertex chamber made of 100 kg stainless steel (316L), as a function of time.

In the shutdown between LHC runs, the radioactive nuclides produced during the run decay. This process is particularly important for the short-lived nuclides, ^{59}Fe ($T_{1/2} = 45$ d) and ^{58}Co ($T_{1/2} = 72$ d), which largely disappear during this period. The longer-lived nuclides, ^{54}Mn ($T_{1/2} = 300$ d) and in particular ^{60}Co ($T_{1/2} = 5.3$ yr), will still be present when the next run starts. Therefore, their concentration accumulates with time, especially in the case of ^{60}Co.

This is illustrated in Figure 2, which shows the total induced radioactivity, and its contributing components, of a 100 kg steel vertex chamber as a function of time. At the end of the first run, the total activity is about 1 MBq (27 μCi). This drops by a factor of 3 by the time the second run is about to start. ^{60}Co is still a minor component at that stage. However, as time goes by, the relative importance of ^{60}Co gradually increases, and after 10 years of running this nuclide completely dominates the induced activity, even for a chamber made of completely cobalt-free steel. As illustrated above, any trace of cobalt in the steel itself will further increase this tendency, and thus the long-term radioactivity of the vertex chamber. For example, a chamber made of steel that contains 1% of cobalt would be three times as radioactive after 10 years of operation as indicated in Figure 2.

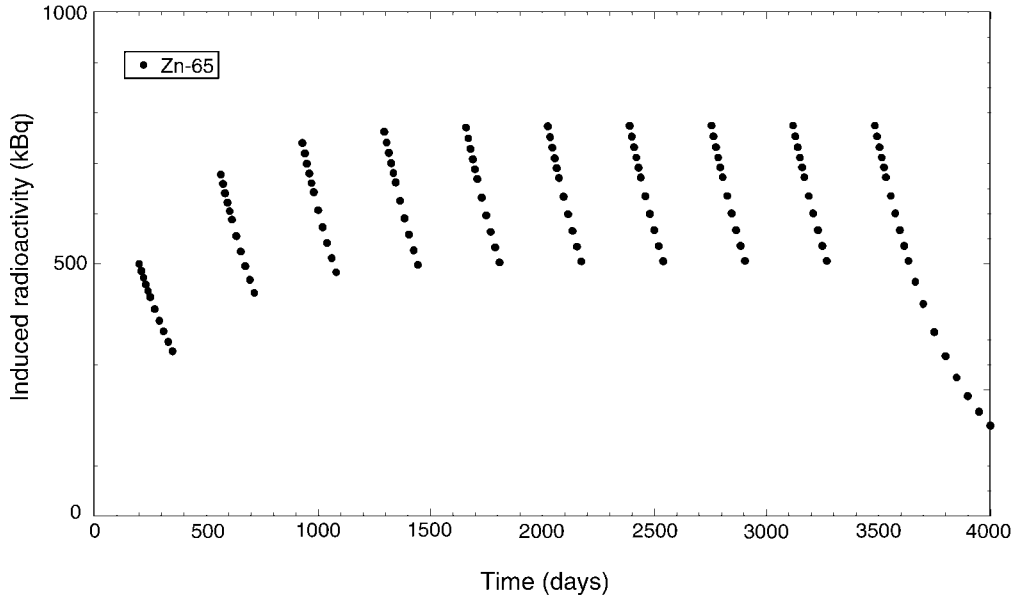

Figure 3: The specific radioactivity of a vertex chamber made of 100 kg aluminium (AMP 8000), as a function of time.

We have performed the same calculations for a vertex chamber made of aluminium. It turns out that the process that largely dominates the (long-term) induced radioactivity in that case is one that involves the zinc admixture: ^{64}Zn (n,γ) ^{65}Zn. This zinc isotope has a half-life of 244 days and has a 50% probability of decaying by emitting a 1.115 MeV γ ray. The target isotope ^{64}Zn makes up 49% of natural zinc. The precise zinc content of the aluminium is thus crucial for the activation of the chamber.

We also checked the production of ^{60}Co, which may proceed through the reaction ^{63}Cu (n, α) ^{60}Co in this case. However, the cross section for this process is three orders of magnitude smaller than that for the production of ^{65}Zn, which makes its contribution to the induced radioactivity insignificant in this case. For a vertex chamber made of AMP 8000, which was the basis of our calculations, we found specific activities that were about a factor of two smaller than for the (cobalt-free) steel chamber discussed above (see Figure 3). However, since an aluminium chamber is typically considerably lighter than a steel one, the weight difference provides a further (proportional) reduction in the total activity of the object.

4 Conclusions

We have calculated the expected levels of induced radioactivity in vertex chambers made of steel (316L) and aluminium (AMP 8000), based on first principles. In both cases, the induced radioactivity is dominated by nuclides produced in reactions involving admixtures to the main construction elements: Nickel in the case of steel, zinc in the case of aluminium. This shows that the precise composition of the construction material is crucial in this respect. In particular, one should avoid any traces of cobalt, if steel is the material of choice. Aluminium is clearly a better construction material, from this perspective. For equal mass objects, one gains a factor of at least two with aluminium. Moreover, the long-term residual activity is much higher in the case of steel, because of the half-lives of the dominant nuclides (5.3 yr in the case of steel, 8 months in the case of aluminium).

Finally, it should be emphasized that the levels of induced radioactivity, calculated on the basis of the particle fluxes from Reference [2], are not alarmingly high. Most definitely, they do *not* preclude maintenance work during shutdowns, provided that proper precautions are taken.

References

[1] C. Leroy *et al. , Nucl. Instr. and Meth.* **A243** (1986) 123.

[2] V. Talanov, *Radiation Environment at the LHC-b Vertex Detector Area*, internal note LHCb 98-019 (1998).