EDMS No. 601754

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

Safety Commission

Technical Note
CERN-SC-2005-049-RP-TN
Version 1.1

Induced radioactivity in the target and solenoid of the TT2A mercury target experiment (nToF11)

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Abstract

This note discusses the expected amount of induced radioactivity in the various components of the target-solenoid assembly of the proposed nToF11 experiment in the TT2A tunnel of the PS complex. The dose rates expected for various decay times after the end of the irradiation are calculated. The environmental impact of the release of the activated nitrogen used to cool the solenoid is evaluated. Some recommendations are given.

CERN, 1211 Geneva 23, Switzerland
16 June 2005

1. Introduction

In the framework of the feasibility study for a future neutrino-production facility (a neutrino “super-beam” or a neutrino factory), an experiment has been proposed (identified as nToF11) as a proof-of-principle demonstration of a target system based on a free mercury jet suitable for use in a 4-MW pulsed proton beam [1]. The aim is to study the pion production and target behaviour of a mercury jet target irradiated by 24 GeV protons from the CERN Proton Synchrotron (PS). The experiment is to be installed in the TT2A transfer line from the PS to the n_TOF facility, downstream of the main shielding wall separating the PS side from the n_TOF side of TT2A and upstream of the n_TOF target area.

In the planned experiment a 24 GeV/c beam pulse with an intensity of 3 x 10^{13} protons hits a mercury jet target 30 cm long and 1 cm in diameter approximately once per hour, for a total of 100 PS pulses. The duration of the experiment will be about two weeks. As the target recirculating system is still under design, the exact amount of mercury which will be irradiated is not yet known, but it is presently estimated to be about 25 l [2]. The mercury jet is projected at the centre of a normal-conducting solenoid consisting of three concentric copper coils housed in a cryostat filled with liquid nitrogen (Figure 1). The solenoid operates in a pulsed mode and it is cooled to cryogenic temperature in order to achieve a 15 T magnetic field at the time of the proton pulse.

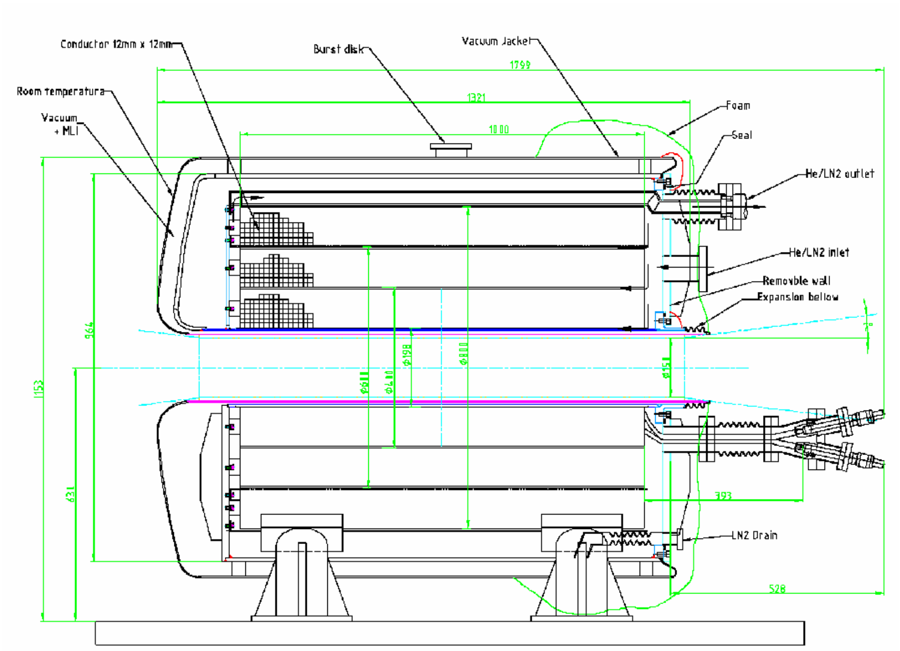

Figure 1. Layout of the 15 T pulsed solenoid (courtesy A. Fabich and H. kirk).

The target, the cryostat and the liquid nitrogen will be activated by the approximately 3 x 10^{15} total protons hitting the target. The liquid nitrogen present in the cryostat at the time the proton pulse hits the target jet will evaporate to gas and will have to be released. This note provides an estimate of the induced radioactivity in the mercury and in components of the cryostat at the end of the experimental run, of the dose rates from the target and cryostat, and of the environmental impact caused by the release of the activated N_2 gas.

2. Calculations

The calculations were performed with the FLUKA Monte Carlo code [3, 4]. The target-solenoid assembly shown in Figure 1 was reproduced quite closely in the FLUKA geometry, modelling individually the three copper coils and the two stainless steel vessels of the cryostat. The outer vacuum vessel is 103.55 cm in diameter, 122.5 cm long and 4.75 mm thick. It is made of AISI 304 L steel with the following chemical composition by weight: 18.5% Cr, 11.5% Ni, 0.03% C, 1% Si, 2% Mn, 0.045% P, 0.03% S, the remainder is Fe. The inner vessel is 93.86 cm in diameter, 115 cm long and 12.7 mm thick. It is made of AISI 316 L with the following chemical composition by weight: 17.5% Cr, 12.5% Ni, 0.03% C, 1% Si, 2% Mn, 2% Mo, 0.05% N, 0.03% P, 0.01% S, the remainder is Fe [5]. The space between the two vessels is vacuum. The inner bore of the cryostat has a diameter of 15 cm and a wall thickness of 5 mm. The three concentric coils are 100 cm long, 9.5 cm thick and have inner diameters of 16 cm, 36 cm and 56 cm, respectively. Part of the inner vessel, including the 5 mm gaps between the coils, is filled with 120 l of liquid nitrogen, the outer part of its volume being filled with air.

The target is a mercury cylinder 30 cm long and 1 cm in diameter placed at the centre of the cryostat bore on the beam axis. The target-solenoid assembly is located in a rectangular tunnel with approximately the dimensions of the TT2A tunnel, 4 m wide and 6 m high. The tunnel walls are made of standard CERN concrete 1 m thick. The beam axis is 1.5 m above the floor and 1.5 from the right tunnel wall (looking downstream).

Scoring of the residual radionuclides was performed with the RESNUCLE option of FLUKA in the target, in the three coils and in the two vessels of the cryostat separately. The total radioactivity (Bq) was scored in the target and in the liquid nitrogen, and the specific activity (Bq/cm^3) in the coils and vessels. The FLUKA results for copper and stainless steel were processed with routines developed by A. Ferrari, M. Magistris and S. Roesler (CERN) to calculate the build-up of radioactivity from 100 pulses each containing 3 x 10^{13} protons, with 1 h waiting time between successive pulses. Because these routines cannot presently handle the large number of radionuclides generated in high-Z materials, the activation of mercury was calculated for a continuous irradiation of either 100 hours or one month with 3.2 x 10^{15} protons in total. This approach introduces some uncertainties with respect to the real, pulsed operation, only for short-lived radionuclides and short waiting times. The prediction of the residual radioactivity for cooling times longer that a few days is not affected.

The prompt radiation in the target, solenoid and surrounding areas was also scored. Figure 2 shows the instantaneous dose equivalent (Sievert) generated by a single pulse of 3 x 10^{13} protons of 24 GeV/c. Apart from the obviously very intense radiation field around the target (of the order of 1000 Sv integrated over the pulse), the area a few metres downstream of the solenoid still shows several Sievert per pulse.

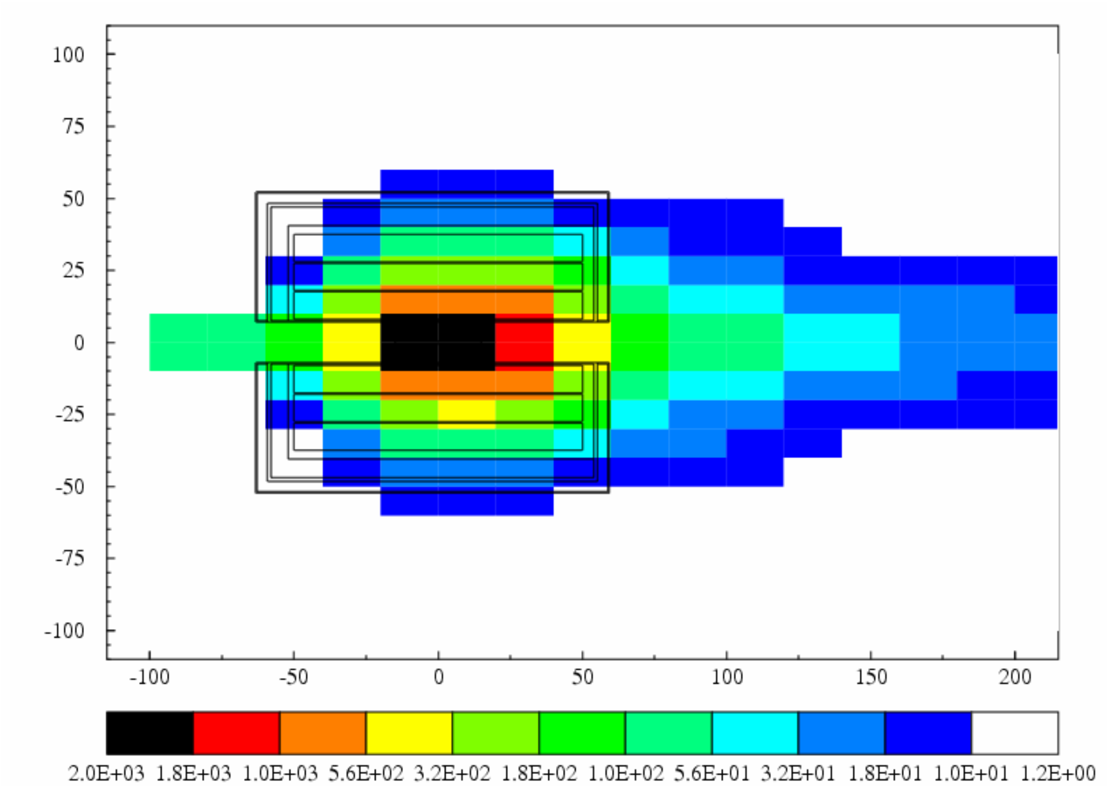

Figure 2. Prompt radiation (Sv per pulse) in the target, solenoid and surrounding area.

3. Induced radioactivity in the target and solenoid

The radionuclides that will be generated in the target, in the coils and in the cryostat are listed in the Appendix for decay times from one day to ten years.

The total radioactivity in the target (which is independent of the amount of mercury circulating in the system) is plotted in Figure 3 as a function of decay time. The residual activity in mercury was also estimated in a previous study by H. Kirk [2] with MCNPX [6] for one month continuous irradiation followed by one month wait. The values found with MCNPX are compared with those calculated with FLUKA in Table 1 for the same irradiation cycle. Although there are some discrepancies in the activity of the individual nuclides (50% to a factor of 3 for the most abundant ones – ^{195}Au, ^{189}Ir and ^{188}Ir – and up to a factor of ten for the least abundant ones – ^{113}In and ^{113}Sn), the total activity calculated with MCNPX (90 MBq from isotopes contributing at least 1% of the total activity) is consistent with the one calculated with FLUKA (180 MBq). The factor of 2 difference may be explained by differences in the geometry set-up and in the codes.

The Appendix gives the activity in mercury after a constant irradiation of 100 hours (approximately 4 days) with 3.2×10^{15} protons in total. After one hour of cooling time the dominant radionuclides are ^{199m}Hg, ^{193}Au and ^{197}Hg. Nevertheless most of the activity is due to a mixture of more than 50 nuclides. After one day ^{193}Au and ^{197}Hg are the two most radioactive nuclides. After one month of decay the most important radionuclides are ^{188}Ir, ^{189}Ir and ^{188}Pt [(1)]. On a time scale of a few years the residual radioactivity is mostly due to ^{3}H and ^{193}Pt.

[(1)] These values cannot be directly compared with those in table 1, which are calculated for a one month irradiation followed by a one month cooling period.

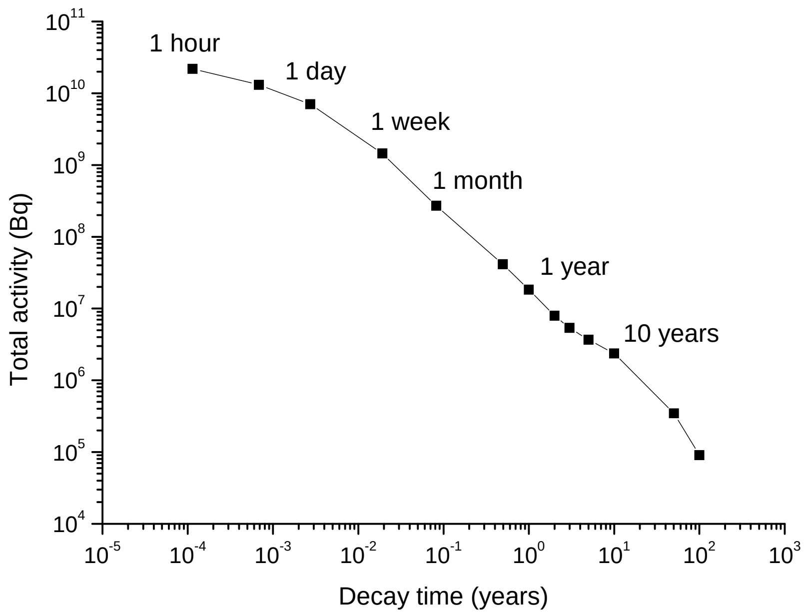

Figure 3. Total induced radioactivity in the mercury target at the end of an irradiation of 100 hours with $3.2 \cdot 10^{15}$ total number of protons for decay times up to 100 years.

Table 1. The most important radionuclides responsible for the residual radioactivity in the target after 30 days of continuous irradiation with 1.23×10^9 protons per second (i.e., 3.2×10^{15} protons in total) and one month waiting time. MCNPX data courtesy H. Kirk, Brookhaven National Laboratory (USA). The total activity calculated with MCNPX is about 90 MBq, that calculated with FLUKA is about 180 MBq.

Nuclide	FLUKA (Bq)	MCNPX (Bq)	Nuclide	FLUKA (Bq)	MCNPX (Bq)
^{195}Au	1.62E+07	1.15E+07	^{3}H	3.48E+06	
^{189}Ir	1.50E+07	6.29E+06	^{131}Cs	2.94E+06	
^{178}Ta	1.06E+07		^{149}Eu	2.58E+06	
^{188}Ir	1.05E+07	3.55E+06	^{171}Lu	2.25E+06	
^{183}Re	1.01E+07		^{151}Gd	2.16E+06	
^{203}Hg	9.82E+06	1.59E+07	^{167}Tm	2.05E+06	
^{185}Os	9.24E+06		^{159}Dy	1.99E+06	
^{188}Pt	8.75E+06		^{127}Xe	1.88E+06	5.18E+06
^{175}Hf	6.80E+06		^{125}I	1.61E+06	5.18E+06
^{181}W	6.67E+06		^{121}Te	1.51E+06	8.51E+06
^{169}Yb	6.50E+06		^{103}Rh	1.50E+06	4.81E+06
^{146}Eu	4.33E+06	2.11E+06	^{105}Ag	1.25E+06	7.40E+06
^{147}Eu	4.05E+06	2.41E+06	^{113}In	8.09E+05	8.51E+06
^{146}Gd	3.93E+06		^{113}Sn	8.09E+05	8.51E+06

The specific activities (activities per unit volume) in the three coils and in the inner and outer vessels of the cryostat are shown in Figures 4 and 5. For the first few days, in the inner coil most of the activity is due to the short-lived ($T_{1/2}$ = 12.7 h) ^{64}Cu. After one month of cooling down the main contributors are ^{58}Co (45%) and ^{51}Cr

(15%), after one year the dominant nuclides are ^{57}Co (28%), ^{54}Mn (17%), ^{55}Fe (17%) and ^{58}Co (13%) and on time scales of a few years the residual radioactivity is mainly due to ^{55}Fe, ^{60}Co and ^{63}Ni. For the medium coil the main radionuclides are the same, although the relative contributions change somehow. For the outer coil the situation is also similar, with some exceptions (the main contributors are ^{58}Co and ^{57}Co after one month of decay and ^{57}Co, ^{58}Co, ^{55}Fe, ^{60}Co and ^{54}Mn after one year). These slight differences can be explained by the fact that the secondary radiation field coming from the target and impinging on the outer coil is modified by the interaction with the inner coils.

As for the inner vessel, after one hour of cooling time 42% of the total activity is due to the short-lived ($T_{1/2}$ = 2.6 h) ^{56}Mn. After one day ^{51}Cr and ^{52}Mn contribute about 25% each of the total activity, with ^{57}Ni and ^{48}V each providing about 10%. After one month of decay the most important radionuclides are ^{51}Cr (contributing for about 45% of the total), ^{58}Co (13%) and ^{48}V (about 10%). On a time scale of a few years the residual radioactivity is mostly due to ^{55}Fe and ^{54}Mn, later to mostly ^{60}Co and on time scales of several tens of years to ^{3}H and ^{63}Ni.

In the outer vessel of the cryostat, after one hour of cooling time a large fraction (64%) of the total activity is due to ^{56}Mn. After one day the main radionuclides are ^{51}Cr (37%) and ^{52}Mn (23%), with ^{57}Ni and ^{48}V each contributing for about 8%. After one month of decay more than half of the activity (57%) is due to ^{51}Cr, with much lower contributions from ^{48}V (8%), ^{58}Co (7%), ^{54}Mn (7%) and ^{55}Fe (5%). On a time scale of a few years the residual radioactivity is mostly due to ^{55}Fe and ^{54}Mn, after 10 year to ^{55}Fe and on time scales of tens of years to ^{3}H and ^{63}Ni.

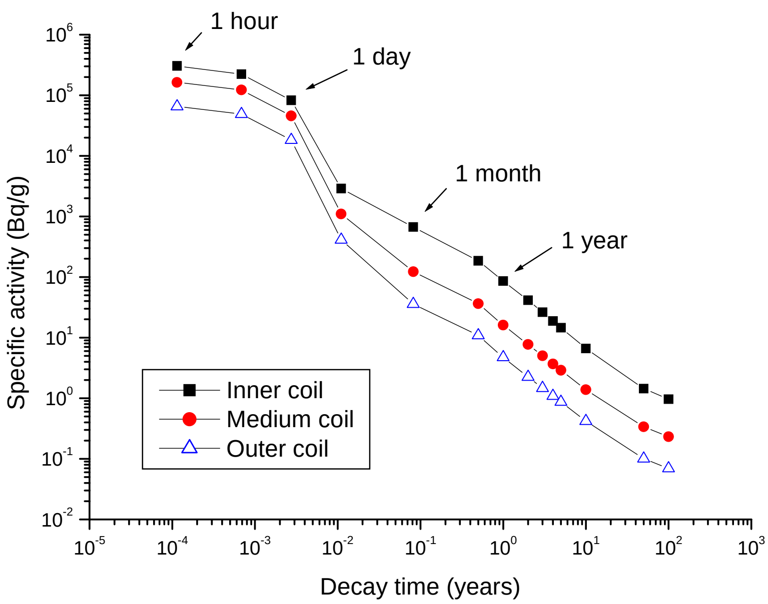

Figure 4. Specific activity in the three copper coils of the solenoid at the end of the experiment for decay times of up to 100 years.

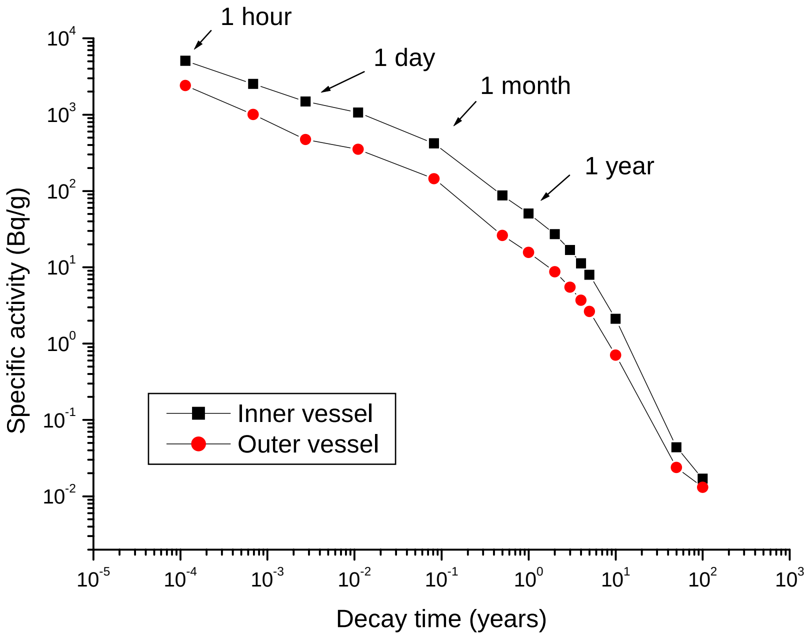

Figure 5. Specific activity in the two stainless steel vessels of the cryostat at the end of the experiment for decay times of up to 100 years.

4. Dose rates

The ambient dose equivalent rates from the target and solenoid after irradiation with 100 PS pulses were calculated with MicroShield [7], using as input data the activities of the main radionuclides present in each material as listed in the Appendix.

If it is supposed that at the end of the experiment the 25 l of irradiated mercury are stored in a spherical tank of 18 cm diameter, the dose rate at 1 m from the tank will be about 30 µSv/h after one day of decay and about 1.5 µSv/h after one month.

The dose rate from the cryostat will essentially be due to the radioactivity induced in the outer vessel. At 1 m distance the dose rate will be about 3 µSv/h after one hour of decay [(2)] and 0.5 µSv/h after one day. The most activated component will be the inner coil, which does not contribute to the dose rate outside the cryostat as it is shielded by the two outer coils and by the two stainless steel vessels. However, if unshielded the dose rate at 1 m distance will be about 100 µSv/h after one hour of cooling, and will reduce to 30 µSv/h after one day and to 3 µSv/h after one week. One should thus wait for a few days before disassembling the cryostat, if this is needed.

5. Induced radioactivity in the liquid nitrogen and the environmental impact of its release

At the moment the proton pulse hits the mercury target, the liquid nitrogen contained in the cryostat will evaporate into gas and will have to be released into the

[(2)] The radionuclides present after one hour are not listed in the Appendix atmosphere. The radiological impact obviously depends on the amount of radioactivity, which in turn depends on the amount of nitrogen that is irradiated.

Three scenarios were investigated:

1) the cryostat is completely filled with 120 l of LN_2 during the PS pulse. All of the activated nitrogen is released in gaseous form after each irradiation;

2) the cryostat is completely filled with 120 l of LN_2 during the PS pulse, but only 10% evaporates into gas and it is released after each pulse. The rest remains in the cryostat and it is re-used (and thus re-irradiated). The cryostat is refilled before the next irradiation with 10% fresh LN_2;

3) all of the LN_2 is removed from the cryostat before the irradiation, only about 1% remaining at the bottom of the cryostat during the PS pulse. Only this small fraction is activated and released as radioactive gas. This is the most likely scenario as proposed by the nToF11 collaboration [2].

Scenario 1: irradiation of 120 l of $\boldsymbol{LN_2}$

The total radioactivity in 120 l of LN_2 for 3 x 10^{13} protons at 24 GeV/c hitting the mercury target is given in Table 2 along with the contribution from individual isotopes, for various waiting times. Essentially all of the activity is due to the comparatively short-lived positron emitters ^{13}N and ^{11}C, with ^{14}O also present in the first few minutes. For 100 PS pulse, the total radioactivity released into the atmosphere will be 100 times the values given in Table 2.

Table 2. Total radioactivity (Bq) in 120 l of LN_2 for 3 x 10^{13} protons at 24 GeV/c hitting a 30 cm thick, 1 cm diameter mercury jet target located at the centre of the solenoid.

Radionuclide / $T_{1/2}$		Waiting time (s)			
		60	600	1800	3600
^{13}N	9.96 m	2.6 x 10^9	1.4 x 10^9	3.5 x 10^8	4.3 x 10^7
^{11}C	20.39 m	2.9 x 10^8	2.1 x 10^8	1.1 x 10^8	3.9 x 10^7
^{14}O	70.61 s	2.4 x 10^8	1.2 x 10^6	–	–
^{10}C	19.25 s	1.4 x 10^8	–	–	–
^{11}Be	13.81 s	1.2 x 10^7	–	–	–
^{7}Be	53.29 d	5.1 x 10^4	5.1 x 10^4	5.1 x 10^4	5.1 x 10^4
^{3}H	12.33 y	3.3 x 10^3	3.3 x 10^3	3.3 x 10^3	3.3 x 10^3
^{14}C	5730 y	1.1 x 10^2	1.1 x 10^2	1.1 x 10^2	1.1 x 10^2
Total		3.3 x 10^9	1.6 x 10^9	4.6 x 10^8	8.2 x 10^7

Scenario 2: partial irradiation of the $\boldsymbol{LN_2}$

In this scenario it is assumed that the cryostat is filled with 120 l of LN_2 during the PS pulse, about 10% of the irradiated liquid evaporates into gas and it is released after each pulse, then the cryostat is refilled with the missing nitrogen before the next pulse. Under these conditions 90% of the LN_2 stays in the vessel after the pulse and it is re-irradiated. For each radionuclide the total released activity A_{TOT} is given by:

$$A_{TOT} = \sum_{j=1}^{N} A_j$$

in which A_j is the activity released after the j-th PS pulse:

$$A_j = 0.1 A_0 \exp(-\lambda t_w) \sum_{i=0}^{N-1} [0.9 \exp(-\lambda T_w)]^i$$

and

A_0 = activity produced in 120 l of LN_2 within one PS pulse,
t_w = waiting time before the activated N_2 gas is released after the pulse,
T_w = time between two PS pulses.

The total released activity is given in Table 3 for two cases, t_w = 15 minutes and T_w = 30 minutes and t_w = 30 minutes and T_w = 1 hour. In both cases the activity is essentially coming from ^{13}N and ^{11}C.

Table 3. Total radioactivity (Bq) in LN_2 released after 100 PS pulses of 3 x 10^{13} protons at 24 GeV/c, assuming that 10% of the nitrogen is released after each pulse and the rest is re-irradiated (see text).

Radionuclide / $T_{1/2}$		t_w=15 min, T_w=30 min	t_w=30 min, T_w=60 min
^{13}N	9.96 m	1.1 x 10^{10}	3.5 x 10^{9}
^{11}C	20.39 m	2.6 x 10^{9}	1.2 x 10^{9}
^{14}O	70.61 s	6.2 x 10^{5}	–
^{7}Be	53.29 d	5.1 x 10^{6}	5.1 x 10^{6}
^{3}H	12.33 y	3.3 x 10^{5}	3.3 x 10^{5}
^{14}C	5730 y	1.1 x 10^{4}	1.1 x 10^{4}
Total		1.4 x 10^{10}	4.7 x 10^{9}

Scenario 3: minimum irradiation

Under the assumption that most of the LN_2 is removed from the cryostat before the pulse and that only about 1% remains inside and becomes activated, the total released activity after each pulse is approximately 1/100 of the values given in Table 2. For 100 pulses the total radioactivity released in the environment is 100 times such values as given in Table 4.

Table 4. Total radioactivity (Bq) in nitrogen released after 100 pulses of 3 x 10^{13} protons at 24 GeV/c under the assumption that only 1% of the LN_2 stays in the cryostat and it is irradiated with each pulse.

	Waiting time (s)			
	60	600	1800	3600
Total activity (Bq)	3.3 x 10^{9}	1.6 x 10^{9}	4.6 x 10^{8}	8.2 x 10^{7}

In reality the activity will be less, as these values are simply scaled from those calculated for scenario 1, where the cryostat is uniformly filled with nitrogen and the activity in Table 2 is the average over 120 l of LN_2. In scenario 3 the residual LN_2 would be located at the bottom of the vessel and thus would be farther from the target and shielded by the coils.

6. Conclusions and recommendations

The analysis of the expected amount of induced radioactivity in the mercury jet target, in the cryostat and in the liquid nitrogen of the nToF11 experiment has shown that there are no fundamental objections to run the experiment with respect to this issue, provided the following measures area taken, in particular for the release of the activated nitrogen gas.

Dose rates

In terms of external exposure, handling of the irradiated mercury and of the cryostat will not represent a particularly high radiation hazard. One should wait for a few days before disassembling the cryostat, if this will be at all needed, in order to reduce the radiation exposure due to the inner coil, which is the most activated component. The most important issue is the contamination risk presented by mercury, which must be properly contained.

Release of the activated N_2 gas

The activated N_2 gas should not be released locally in the TT2A tunnel as this tunnel is connected to the ISR tunnel where people are normally present. The activated gas must be released into the atmosphere via the ventilation stack of the adjacent TT10 tunnel, which is equipped with a radiation monitoring station. The activities calculated in section 5 are to be compared with the annual released of short-lived beta emitters from the TT10 stack due to the operation of the Meyrin accelerators and of other CERN experimental facilities. In 2003 this value was 3.7 TBq [8]. It is considered that a total release from the nToF11 experiment of up to 1% of this value (37 GBq) is acceptable [9], provided that such release does not occur in a “spike” (to avoid setting off a false alarm at the gate monitor installed at the tunnel close to building 54, which is just downwind of the TT10 stack). The total activity released in scenario 3 is well within the 37 GBq constraint. As for scenario 2, the total amount of radioactivity released depends not only on waiting time but also on the interval between pulses (a shorter interval can substantially increase the release). For the two cases shown in Table 2 the total activity released in the course of the experiment is also within the given constraint. On the other hand, scenario 1 is not acceptable.

If the n_TOF target area will be equipped with a ventilation system and stack before the start-up of the nToF11 experiment, the release of the activated N_2 gas can be done via this stack. The fact that the path from the solenoid to the stack mouth will be shorter as compared with the TT10 path – so that the radioactive decay will be lower – will be compensated by the larger distance of the stack from the gate monitor and by the fact that the latter is not directly downwind of the former [9].

Acknowledgements

We wish to thank A. Fabich, A. Ferrari, Th. Otto, S. Roesler, P. Vojtyla (CERN) and H. Kirk (BNL) for useful discussions.

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Appendix

Radionuclide inventory in the target (total activity in Bq), in the three copper coils and in the two stainless steel vessels of the cryostat (specific activity in Bq/cm^3) for decay times of one day, one month, one year and ten years. The tables list the radionuclides that are responsible for 90% of the induced radioactivity. For copper and stainless steel the calculations were done for 100 pulses of 3 x 10^{13} protons, one pulse per hour, for mercury a constant irradiation of 100 hours with 3.2 x 10^{15} protons in total was adopted.

Mercury target

After one day of cooling

Main contributors to total activity

	A	Tot. Yield Bq			T1/2
Hg	197	7.205E+08	+/-	0.4 %	2.309E+05s
Au	193	4.399E+08	+/-	0.4 %	6.354E+04s
Pt	191	4.252E+08	+/-	0.7 %	2.506E+05s
Hg	197m	2.908E+08	+/-	0.6 %	8.568E+04s
Re	182	2.133E+08	+/-	1.0 %	2.304E+05s
Hg	195	2.077E+08	+/-	0.5 %	3.564E+04s
Au	194	1.969E+08	+/-	1.5 %	1.369E+05s
Ir	186	1.819E+08	+/-	1.0 %	5.990E+04s
Hg	195m	1.784E+08	+/-	0.7 %	1.498E+05s
Os	182	1.769E+08	+/-	1.0 %	7.956E+04s
Re	181	1.633E+08	+/-	1.3 %	7.164E+04s
Au	199	1.553E+08	+/-	0.8 %	2.712E+05s
Au	198	1.544E+08	+/-	0.9 %	2.327E+05s
Ta	177	1.541E+08	+/-	1.6 %	2.036E+05s
Lu	170	1.317E+08	+/-	1.8 %	1.728E+05s
Ir	185	1.293E+08	+/-	0.9 %	5.184E+04s
Pt	188	1.287E+08	+/-	1.0 %	8.813E+05s
Ir	187	1.248E+08	+/-	1.0 %	3.780E+04s
Hf	173	1.233E+08	+/-	1.7 %	8.496E+04s
Au	196	1.220E+08	+/-	0.8 %	5.342E+05s
Ir	188	1.211E+08	+/-	1.0 %	1.494E+05s
Ir	189	1.186E+08	+/-	0.8 %	1.140E+06s
Er	165	1.067E+08	+/-	1.6 %	3.730E+04s
Tm	166	1.054E+08	+/-	1.6 %	2.772E+04s
Os	183	1.052E+08	+/-	1.2 %	4.680E+04s
Lu	169	9.599E+07	+/-	1.4 %	1.226E+05s
Yb	166	9.391E+07	+/-	1.6 %	2.041E+05s
Au	198m	9.106E+07	+/-	1.3 %	1.987E+05s
Tm	165	8.101E+07	+/-	1.6 %	1.082E+05s

Total activity : 7.052E+9 Bq

After one month of cooling

Main contributors to total activity

	A	Tot. Yield Bq			T1/2
Ir	189	2.689E+07	+/-	0.8 %	1.140E+06s
Ir	188	2.160E+07	+/-	1.0 %	1.494E+05s
Pt	188	1.794E+07	+/-	1.0 %	8.813E+05s
Au	195	1.704E+07	+/-	0.4 %	1.608E+07s
Ta	178	1.558E+07	+/-	1.1 %	5.586E+02s
W	178	1.557E+07	+/-	1.1 %	1.866E+06s
Hg	203	1.185E+07	+/-	1.8 %	4.027E+06s
Re	183	1.145E+07	+/-	1.1 %	6.048E+06s
Os	185	1.019E+07	+/-	0.9 %	8.087E+06s
Yb	169	8.483E+06	+/-	1.4 %	2.767E+06s
Hf	175	7.732E+06	+/-	1.5 %	6.048E+06s
W	181	7.201E+06	+/-	1.3 %	1.047E+07s
Eu	147	5.717E+06	+/-	1.5 %	2.082E+06s

Total activity : 2.71E+8 Bq

Mercury target (continued)

After one year of cooling

Main contributors to total activity

	A	Tot. Yield Bq			T1/2
Au	195	4.899E+06	+/-	0.4 %	1.608E+07s
H	3	3.326E+06	+/-	0.4 %	3.888E+08s
W	181	1.063E+06	+/-	1.3 %	1.047E+07s
Ta	179	9.353E+05	+/-	1.4 %	5.645E+07s
Os	185	8.550E+05	+/-	0.9 %	8.087E+06s
Lu	173	7.946E+05	+/-	1.6 %	4.320E+07s
Lu	172	6.540E+05	+/-	1.3 %	5.789E+05s
Hf	172	6.476E+05	+/-	1.3 %	5.897E+07s
Dy	159	4.267E+05	+/-	1.9 %	1.248E+07s
Re	183	4.168E+05	+/-	1.1 %	6.048E+06s
Sm	145	4.051E+05	+/-	1.7 %	2.938E+07s
Gd	151	3.582E+05	+/-	1.8 %	1.071E+07s
Pm	143	3.165E+05	+/-	2.0 %	2.290E+07s

Total activity : 1.82E+7 Bq

After ten years of cooling

Main contributor to total activity

	A	Tot. Yield Bq			T1/2
H	3	2.007E+06	+/-	0.4 %	3.888E+08s
Pt	193	1.430E+05	+/-	0.4 %	1.577E+09s
Pm	145	3.173E+04	+/-	1.7 %	5.582E+08s
Ta	179	2.878E+04	+/-	1.4 %	5.645E+07s
Ba	133	2.430E+04	+/-	2.9 %	3.318E+08s
Lu	172	2.336E+04	+/-	1.3 %	5.789E+05s
Hf	172	2.313E+04	+/-	1.3 %	5.897E+07s
Gd	148	1.634E+04	+/-	1.8 %	2.353E+09s

Total activity : 2.37E+6 Bq

Inner copper coil

After one day of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Cu	64	0.808E+05	+/-	0.2 %	12.70h
Mn	52	0.380E+03	+/-	0.8 %	5.59d
V	48	0.139E+03	+/-	1.1 %	15.97d
Co	58	0.398E+03	+/-	0.4 %	70.82d
Co	56	0.551E+02	+/-	0.8 %	77.27d
Ni	57	0.707E+02	+/-	2.7 %	35.60h
Sc	48	0.237E+02	+/-	5.1 %	43.67h

Total activity : 0.8262E+05 Bq/cm^3

After one month of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	58	0.300E+03	+/-	0.4 %	70.82d
Cr	51	0.104E+03	+/-	0.6 %	27.70d
Co	57	0.571E+02	+/-	0.4 %	271.79d
Co	56	0.427E+02	+/-	0.7 %	77.27d
V	48	0.398E+02	+/-	1.1 %	15.97d
Mn	54	0.304E+02	+/-	0.5 %	312.12d
Fe	59	0.230E+02	+/-	0.9 %	44.50d
Fe	55	0.181E+02	+/-	0.5 %	2.73y
Mn	52	0.104E+02	+/-	0.8 %	5.59d

Total activity : 0.6696E+03 Bq/cm^3

After one year of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	57	0.243E+02	+/-	0.4 %	271.79d
Mn	54	0.145E+02	+/-	0.5 %	312.12d
Fe	55	0.143E+02	+/-	0.5 %	2.73y
Co	58	0.113E+02	+/-	0.4 %	70.82d
Co	60	0.887E+01	+/-	0.5 %	5.27y
V	49	0.613E+01	+/-	0.6 %	338.00d
Co	56	0.212E+01	+/-	0.7 %	77.27d

Total activity : 0.8608E+02 Bq/cm^3

After ten years of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	60	0.272E+01	+/-	0.5 %	5.27y
Ni	63	0.178E+01	+/-	0.2 %	100.10y
Fe	55	0.146E+01	+/-	0.5 %	2.73y

Total activity : 0.6596E+01 Bq/cm^3

Medium copper coil

After one day of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Cu	64	0.453E+05	+/-	0.2 %	12.70h
Co	58	0.903E+02	+/-	0.3 %	70.82d
Mn	52	0.473E+02	+/-	2.2 %	5.59d
V	48	0.123E+02	+/-	1.5 %	15.97d
Ni	57	0.117E+02	+/-	5.0 %	35.60h
Co	56	0.980E+01	+/-	1.4 %	77.27d

Total activity : 0.4559E+05 Bq/cm^3

After one month of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	58	0.680E+02	+/-	0.3 %	70.82d
Cr	51	0.126E+02	+/-	0.9 %	27.70d
Co	57	0.117E+02	+/-	0.7 %	271.79d
Co	56	0.759E+01	+/-	1.4 %	77.27d
Fe	59	0.488E+01	+/-	2.1 %	44.50d
Mn	54	0.486E+01	+/-	1.0 %	312.12d
V	48	0.351E+01	+/-	1.5 %	15.97d
Co	60	0.233E+01	+/-	0.4 %	5.27y

Total activity : 0.1230E+03 Bq/cm^3

After one year of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	57	0.497E+01	+/-	0.7 %	271.79d
Co	58	0.256E+01	+/-	0.3 %	70.82d
Fe	55	0.246E+01	+/-	0.7 %	2.73y
Mn	54	0.231E+01	+/-	1.0 %	312.12d
Co	60	0.207E+01	+/-	0.4 %	5.27y
V	49	0.616E+00	+/-	1.5 %	338.00d
Co	56	0.376E+00	+/-	1.4 %	77.27d

Total activity : 0.1613E+02 Bq/cm^3

After ten years of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	60	0.634E+00	+/-	0.4 %	5.27y
Ni	63	0.431E+00	+/-	0.4 %	100.10y
Fe	55	0.250E+00	+/-	0.7 %	2.73y

Total activity : 0.1390E+01 Bq/cm^3

Outer copper coil

After one day of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Cu	64	0.181E+05	+/-	0.2 %	12.70h
Co	58	0.286E+02	+/-	0.4 %	70.82d
Mn	52	0.108E+02	+/-	3.1 %	5.59d
Ni	57	0.330E+01	+/-	7.8 %	35.60h
Co	56	0.278E+01	+/-	1.7 %	77.27d

Total activity : 0.1822E+05 Bq/cm^3

After one month of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	58	0.215E+02	+/-	0.4 %	70.82d
Co	57	0.359E+01	+/-	0.8 %	271.79d
Cr	51	0.259E+01	+/-	3.5 %	27.70d
Co	56	0.215E+01	+/-	1.7 %	77.27d
Fe	59	0.157E+01	+/-	2.8 %	44.50d
Mn	54	0.127E+01	+/-	1.6 %	312.12d
Co	60	0.743E+00	+/-	1.1 %	5.27y
V	48	0.582E+00	+/-	4.7 %	15.97d

Total activity : 0.3580E+02 Bq/cm^3

After one year of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	57	0.153E+01	+/-	0.8 %	271.79d
Co	58	0.811E+00	+/-	0.4 %	70.82d
Fe	55	0.698E+00	+/-	0.8 %	2.73y
Co	60	0.659E+00	+/-	1.1 %	5.27y
Mn	54	0.605E+00	+/-	1.6 %	312.12d
Co	56	0.106E+00	+/-	1.7 %	77.27d

Total activity : 0.4728E+01 Bq/cm^3

After ten years of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Co	60	0.202E+00	+/-	1.1 %	5.27y
Ni	63	0.129E+00	+/-	0.4 %	100.10y
Fe	55	0.711E-01	+/-	0.8 %	2.73y

Total activity : 0.4201E+00 Bq/cm^3

Inner vessel of cryostat (AISI 316 L)

After one day of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Cr	51	0.403E+03	+/-	0.6 %	27.70d
Mn	52	0.364E+03	+/-	0.9 %	5.59d
Ni	57	0.157E+03	+/-	2.0 %	35.60h
V	48	0.148E+03	+/-	1.4 %	15.97d
Co	58	0.752E+02	+/-	0.5 %	70.82d
Sc	47	0.741E+02	+/-	2.8 %	80.28h
Mn	54	0.340E+02	+/-	0.4 %	312.12d
Co	55	0.324E+02	+/-	3.9 %	17.53h
Sc	48	0.241E+02	+/-	3.3 %	43.67h
Fe	55	0.231E+02	+/-	0.4 %	2.73y
Co	56	0.164E+02	+/-	1.1 %	77.27d

Total activity : 0.1485E+04 Bq/cm^3

After one month of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Cr	51	0.195E+03	+/-	0.6 %	27.70d
Co	58	0.566E+02	+/-	0.5 %	70.82d
V	48	0.422E+02	+/-	1.4 %	15.97d
Mn	54	0.319E+02	+/-	0.4 %	312.12d
Fe	55	0.226E+02	+/-	0.4 %	2.73y
V	49	0.151E+02	+/-	0.6 %	338.00d
Co	57	0.139E+02	+/-	0.9 %	271.79d
Co	56	0.132E+02	+/-	1.2 %	77.27d
Mn	52	0.100E+02	+/-	0.9 %	5.59d

Total activity : 0.4204E+03 Bq/cm^3

After one year of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Fe	55	0.179E+02	+/-	0.4 %	2.73y
Mn	54	0.151E+02	+/-	0.4 %	312.12d
V	49	0.758E+01	+/-	0.6 %	338.00d
Co	57	0.593E+01	+/-	0.9 %	271.79d
Co	56	0.652E+00	+/-	1.2 %	77.27d
Sc	46	0.407E+00	+/-	2.2 %	83.79d

Total activity : 0.5054E+02 Bq/cm^3

After ten years of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3			T1/2
Fe	55	0.182E+01	+/-	0.4 %	2.73y
H	3	0.185E+00	+/-	1.0 %	12.33y
Co	60	0.372E-01	+/-	3.3 %	5.27y
Mn	54	0.103E-01	+/-	0.4 %	312.12d
Sc	44	0.636E-02	+/-	4.7 %	3.93h

Total activity : 0.2105E+01 Bq/cm^3

Outer vessel of cryostat (AISI 304 L)

After one day of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3		T1/2
Cr	51	0.173E+03	+/- 1.3 %	27.70d
Mn	52	0.108E+03	+/- 2.3 %	5.59d
V	48	0.405E+02	+/- 2.6 %	15.97d
Ni	57	0.397E+02	+/- 5.8 %	35.60h
Sc	47	0.181E+02	+/- 10.7 %	80.28h
Co	58	0.143E+02	+/- 2.4 %	70.82d
Mn	54	0.107E+02	+/- 1.3 %	312.12d
Sc	48	0.801E+01	+/- 10.2 %	43.67h
Fe	55	0.774E+01	+/- 1.0 %	2.73y
Co	55	0.717E+01	+/- 10.8 %	17.53h
Co	56	0.430E+01	+/- 5.4 %	77.27d

Total activity : 0.4716E+03 Bq/cm^3

After one month of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3		T1/2
Cr	51	0.837E+02	+/- 1.3 %	27.70d
V	48	0.115E+02	+/- 2.7 %	15.97d
Co	58	0.108E+02	+/- 2.4 %	70.82d
Mn	54	0.100E+02	+/- 1.3 %	312.12d
Fe	55	0.759E+01	+/- 1.0 %	2.73y
V	49	0.465E+01	+/- 2.4 %	338.00d
Co	57	0.385E+01	+/- 2.9 %	271.79d

Total activity : 0.1446E+03 Bq/cm^3

After one year of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3		T1/2
Fe	55	0.601E+01	+/- 1.0 %	2.73y
Mn	54	0.475E+01	+/- 1.3 %	312.12d
V	49	0.234E+01	+/- 2.4 %	338.00d
Co	57	0.164E+01	+/- 2.9 %	271.79d
Co	58	0.405E+00	+/- 2.4 %	70.82d
Co	56	0.170E+00	+/- 5.5 %	77.27d

Total activity : 0.1567E+02 Bq/cm^3

After ten years of cooling

Main contributors to total activity

	A	Tot. Yield Bq/cm^3		T1/2
Fe	55	0.612E+00	+/- 1.0 %	2.73y
H	3	0.513E-01	+/- 3.1 %	12.33y
Co	60	0.874E-02	+/- 11.2 %	5.27y
Mn	54	0.323E-02	+/- 1.3 %	312.12d
Na	22	0.160E-02	+/- 15.3 %	2.60y

Total activity : 0.7050E+00 Bq/cm^3