Ab initio method for dose estimation in a linear electron accelerator

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Abstract

Activation of machine components and air by primary and secondary beams is an inevitable byproduct of a particle accelerator operation. Evaluation of radiation field type and intensity during and shortly after accelerator run is crucial in its planning phase and for obtaining necessary licenses. Final results are usually obtained by employing numerical codes.
In the present paper a transparent ab initio method is given for upper limit dose estimation in a linear electron accelerator. The gamma radiation level is calculated for the linear accelerator FLUTE [1, 2]. In addition possible nuclear reactions are identified and corresponding values for activations are quantified. This simple method was used extensively with success in our official application for an operational license of FLUTE.

Introduction

The accelerator FLUTE (name abbreviation derived from its German name: Ferninfrarot Linac- und Test-Experiment) is currently being set up in cooperation with DESY and PSI and is scheduled to commence operation in 2017 [1]. General safety issues of FLUTE are presented in [2] along with its parameters. In the Phase 1 of FLUTE a 7 MeV photo-injector rf-gun driven by a 6 mJ titanium-sapphire laser is being commissioned. Since the FLUTE hall is walled by thick concrete and no activation whatsoever is expected in the Phase 1, no major radiation protection issues are considered. In the Phase 2, which includes accelerator linac and magnetic bunch compressor, the energy will increase to approximately 42 MeV and hence activation in some components, as well in air has to be considered.

As a linear electron accelerator with end energy below 150 MeV it requires [3] an operational license from the German Authority, meaning in particular that the construction and assembling may be pursued prior to any approval. Despite of that the KIT FLUTE team informed the Authority about the construction intention very early. Since some parameters of FLUTE electron gun (as, e.g., dark currents), crucial for later radiation safety, were not yet known, a procedure of obtaining a sample operational license for FLUTE was elaborated together with the Authority. The procedure included, among others, a straightforward estimation of future radiation effects on staff, as well as a plausible estimation of air activation effects at the Phase 2. Both estimations had to be provided in the construction stage prior to sample operation of Phase 1, in which the characterization of dark currents is expected. To break the circle, the Authority agreed to take the 'usable current' excluding dark currents as a basis for those estimations. Transparent ab initio methods for upper limit dose and activation estimations in a linear electron accelerator were employed.

The beam dump was identified as the most pronounced sources of radiation in both phases. In the following two sections the equivalent radiation dose originating from the bremsstrahlung in the beam dump, as well air activation by bremsstrahlung are elaborated.

Dump

The Dump of Phase 2 of FLUTE consists of an aluminum absorber surrounded by led shielding. The choice of material is based on a minor susceptibility of aluminum for activation [4]. The activation reactions with extraneous elements contained in the absorber can be kept manageable by using a pure aluminum, which is commercially available in very good chemical purity.

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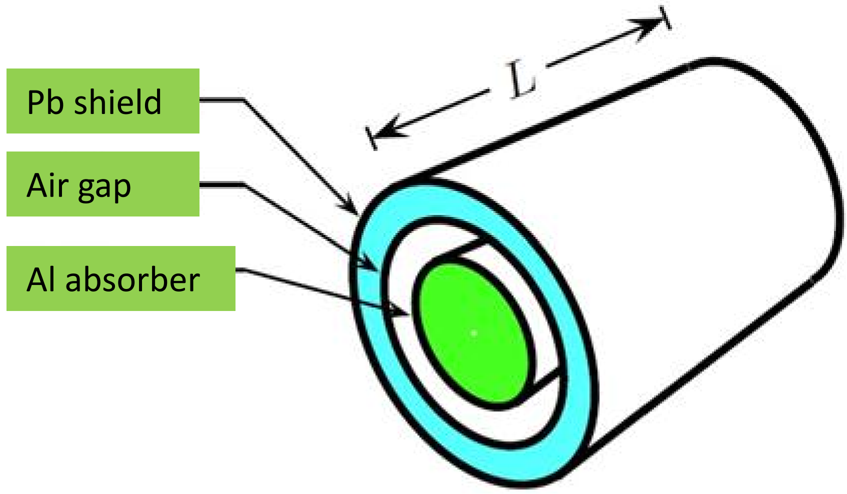

Fig. 1 - The schematic layout of the Dump in the Phase 2 of FLUTE. The cylinder axis is the electron beam direction. Electrons are absorbed in the aluminum core. The bremsstrahlung is attenuated by the led shield. The air gap is thin for reducing activation in the gas slit.

In the absorber a certain fraction of electron energy is converted to gamma radiation field energy. Major part of this energy is adsorbed in the led shielding. In the following the dose and required shielding thickness will be conservatively estimated.

An energetic local unshielded gamma power per surface unit, neglecting the gamma self-shielding in the absorber itself, at the distance r from the beam stop is:

$$W = P_{gamma} / (4 \pi r^2) \quad ; \; P_{gamma} = \alpha \; P_{electron} \qquad (1)$$

with :

$P_{electron}$ – average (DC)-Electron beam power
α – bremsstrahlung conversion efficiency,
P_{gamma} - total unshielded gamma power

For equivalent radiation dose estimation a phantom placed at the istance r is placed. For simplicity a cubic phantom with the edge length d is placed in the radiation field, in volume of which the absorbed gamma energy is assumed to be distributed uniformely. The equivalent radiation dose is $w_T \, d^2 \, W / (\rho d^3)$, where w_T is the radiation weighting factor defined by standard regulation. Substitution of the following numbers: α = 0.33 [4]; $P_{electron}$ =13.5W; r=10m; d=0.4m, ρ=1000kg/m3; w_T =1 for gammas gives an unshielded equivalent dose of 31900 µSv/h, which strongly exceeds the official dose allowance of 0.5 µSv/h. Please note that this energy dose is imaginary and would become quantifiable only in case when no local nor global shieldings were used. On the other hand, the exceedance factor of 63800 defines the required total shielding attenuation. Since the attenuation factor of the concrete walls for high energy gammas is 1860, the local shielding attenuation factor still necessary is at least 34. This could be provided by the absorber shielding with a lead wall as thick as 8 cm. For a rich safety margin and for reasons given in the next section, a 15 cm thickness of the lead shielding was chosen.

Activation of Air in the Hall

In general, thick concrete walls of the FLUTE hall could shift the shielding concept towards a weaker local shielding. But when combined with the large hall dimensions 15 m x 13 m (base) x 12 m (height), this would cause an increased interaction of radiation (mainly gamma and neutrons) with hall air. Staying within maximum concentration limits for activation products the hall would became a driving factor for the cost of air tempering / conditioning. Since FLUTE hall has a closed air circulation and is equipped only with standard air filters, local shielding of chosen components – especially the absorber of the beam dump – has turned to be mandatory.

Table 1 summarizes most prominent nuclear reactions with highest radiological importance in the air under machine operation. The concentration limits, or rather radioactivity budgets, are defined in the Appendix VII of StrlSchV (German Radiation Protection Ordinance) [3].

(Gamma, n)	**($n_{thermal}$, Gamma)**	**(spallation)**
^{15}O ($t_{1/2}$=2 Min)	**^{41}Ar ($t_{1/2}$=1.83 h)**	**^{11}C ($t_{1/2}$=20.3 Min)[3]**
^{13}N ($t_{1/2}$=9.9 Min)	**^{14}C ($t_{1/2}$=5700 y)**	

[3] parent element ^{14}N

Table 1 – Chosen nuclear reactions in the hall air (upper line) which lead to the radioactive products (lower lines) which are safety-relevant during machine operation.

Starting with neutron induced reactions, we can write the total activity (A) in a hall in a macroscopic convention as:

$$A(t) = \Sigma \; N_0 R \; [1-\mathbf{exp}(-\lambda t)] \; ; \quad \Sigma = N \times \sigma \qquad (2)$$

with:

Σ = macroscopic cross section [1/m]
N = atom density of target [atoms/m^3]
σ = microscopic cross section [m^2]
N_0 = total thermal neutron flux per second [1/s]
R = characteristic dimension of system (hall) [m]
λ = decay rate [1/s].

A non-intuitive proportionality of $A(t)$ to the dimension R results from a neutron flux propagating freely over a dimension of a system. In case of a point source and no intensity loss during propagation, the same activation portion occur on each length unit of a propagation cone originating from the source point.

The thermal neutron fluxes N_0 can be obtained from

$$N_0 = P_{gamma} \; Y_{neutron} \; Y_{moderation} \qquad (3)$$

with :

P_{gamma} – total gamma power, see also Equation (1),
$Y_{neutron}$ – neutron yield in the Al-absorber,
$Y_{moderation}$ – moderation factor in the lead shield.

The equation (3) contains a further material parameter $Y_{moderation}$. The numerical value of this factor is chosen based on the theory and experience with reactor shielding [5].

The activity of short living nuclides leads to a saturation of the total activity in the equation (2) during a typical accelerator run time of several hours. This applies to all nuclides listed in Table 1 except for ^{14}C. For this reason, the saturated activities of short-lived isotopes will be used, whereby an exposition over 8 hours will be assumed for ^{14}C.

An activation equation in analogy to equation (2) can also be written for gamma radiation, which we skip here for space reasons. Based on gamma and neutron fluxes, employing cross sections for the given reactions [3] and using average concentrations of parent elements in air, volume activities are calculated and summarized in Table 2. The last column gives the fraction exploited of the activation limits given in the Appendix VII of StrlSchV (German Radiation Protection Ordinance). As seen in the Table 2, the total exploitation turned to be as low as 2.8 percent.

				limit			
nuclide	$\tau_{1/2}$	activation	activation	inhalation	submersion	after App VII	exploited
	h	Bq	Bq/m^3	Bq/m^3	Bq/m^3	Bq/m^3	
^{13}N	1.66E-01	1.00E+05	5.90E+01	n.a.	2.00E+03	2.00E+04	2.95E-03
^{15}O	3.39E-02	1.07E+04	6.30E+00	n.a.	1.00E+03	1.00E+04	6.30E-04
^{14}C	4.99E+07	5.15E+00	3.03E-03	6.00E+00	n.a.	6.00E+01	5.05E-05
^{41}Ar	1.83E+00	6.94E+04	4.08E+01	n.a.	2.00E+02	2.00E+03	2.04E-02
^{11}C	3.39E-01	3.77E+04	2.22E+01	6.00E+02	3.00E+03	6.00E+03	3.69E-03
Sum							2.80E-02

Table 2 – Total and specific activations of the hall air with isotopes most relevant in terms of the Appendix VII of StrlSchV (German Radiation Protection Ordinance). Lower value of either inhaltion or submersion limit is taken and multiplied with factor 10 as foreseen in the Appendix VII for the case air flows in the hall are under 10000 m^3/h. Please note that total exploitation of an allowed activation (lower right number) is very favorable.

Summary

Two transparent and straightforward methods were presented for estimating exposure to radiation on FLUTE staff and air activation in the FLUTE-hall. Both methods can be used for conservative estimations for any linear accelerator. Using those methods a necessary local shielding of the dump was calculated. The expected staff exposition is well below dose limits defined in the German Radiation Protection Ordinance. In addition, the hall air activation stays in the few percent range of limits defined ibidem. The calculation results convinced the Authority to issue the sample license of FLUTE.

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