Activation Calculations with FLUKA for the B*ERL*inPro Vacuum System

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Abstract

In 2012 the Helmholtz-Zentrum Berlin finished the conceptual design report of B*ERL*inPro – a prototype of the Energy Recovery Linac (ERL) technology. The maximum electron energy is 50 MeV, the maximum current is 100 mA (cw), low energy parts of the machine (injector, beam dump line) are operated at about 10 MeV. Due to the high beam power of 5 MW in the ring the machine will be built subterraneously at the BESSYII site. Dedicated assessments concerning radiation protection issues have been done so far in order to determine a detailed radiation safety concept and to obtain the construction permit by using the Monte-Carlo-Code Fluka.
One important issue is the dose caused by activation of the vacuum system, since several accesses into the accelerator hall will be necessary because of a certain amount of maintenance. Therefore different scenarios after switching off the machine are simulated with FLUKA. For these simulations we suppose a constant electron loss of 5 µA/m during operation of the machine and determined the doses at different times after a switch-off for an aluminium alloy and steel. As a result the vacuum system will be constructed out of aluminium except a few parts of steel (due to mechanical reasons).

1. Introduction

At electron accelerators gamma-radiation is caused by electron losses which produce Bremsstrahlung if a certain energy threshold is exceeded. If the photons have energies above ≈10MeV nuclear reactions are possible and therefore activation occurs.
Since this radiation remains after the accelerator is switched off, it has to be considered carefully in order to avoid an additional radiation exposition, e.g. for maintanance workers. One possibility to reduce the activation during planning and construction of a machine is the choice of proper materials. In sect. 2.2 a comparison of the activation of an aluminum and a steel tube shows that the dose rate due to activation for aluminum is a factor of about 100 lower than it is for steel. This is directly considered for the construction for the new energy recovery linac B*ERL*inPro, which is planned at the BESSY site: The vacuum system of the high energy part, which is operated at 50MeV, will be out of aluminum except some dedicated parts. The low energy part will be constructed out of steel (see Sect. 3.2).

2. Calculation of activation

2.1 General considerations

In general the activation rate caused by photons is dependent from the flux density $\Phi(E_P, \vec{r})$ of the photons and the cross section $\sigma(E_P)$:

$$\dot{N}^{+} = \rho \cdot N_L / A \int_0^{V_0} \int_0^{E_0} \sigma(E_P) \cdot \Phi(E_P, \vec{r}) \cdot dE_P dV \qquad (1)$$

(here E_P is the photon energy, ρ is density of nuclei and A is the mass number)

$\dot{N}^{+}$ is the saturation activity which is the highest possible activation for a given nuclear reaction. Below a certain threshold energy the cross section tends to 0. For many important construction materials the threshold energy for photoreactions can be found in Swanson [1].

The well known activation equation (2) takes into account the number of irradiation periods ν, the irradiation time t_B, the decay time t_K and $\lambda = \ln(2)/T_{1/2}$. Note: The decay time t_K is the time after the electron beam is off.

$$A_\nu = \dot{N}^{+} \cdot [1-\exp(-\lambda \cdot t_B)] \cdot \exp(-\lambda \cdot t_K) \cdot \frac{1-\exp[-\nu \cdot \lambda(t_B + t_K)]}{1-\exp(-\lambda(t_B + t_K))} \qquad (2)$$

From this equation one gets the gamma dose rate (here Γ is the isotope dependent radiation constant):

$$\frac{dH}{dt} = \Gamma \cdot \frac{1}{r^2} \cdot A_\nu \qquad (3)$$

$\dot{N}^{+}$ can be calculated with the Monte-Carlo-Code Fluka [2, 3] with the option RESNUCLEII. The resulting nuclei should be selected in respect of half-lifes and decay schemes. By using these formulas it is possible to calculate manually the activation contribution for every single residual nucleus, but especially for alloys with different components this is very intense in time. In addition many isotopes may occur during the decay cascade, which also has to be taken into account. But with Fluka it is also possible to simulate the activation directly for any defined material in one step. After calling the sequence for prompt and delayed decay (RADDECAY) which sets the corresponding biasing and transport conditions, one defines the irradiation profile and different decay times (sometimes also called “cooling times”). The scoring does not change and works like in any other Fluka-file and with one simulation run one obtains for each decay time an extra file that can be analyzed.

2.2 Comparison of the activation of steel and aluminum

The activation of an aluminum and steel alloy is compared for an electron loss of 5µA/m with an electron beam energy of 50 MeV. This electron loss during operation of the new energy recovery linac is the limit of the machine protection system. The intention is to analyze if the use of this aluminum alloy reduces the activation significantly in comparison with steel. (The exact compound is listed in Tab. 1).

Aluminum (Al5080) **densitiy: 2.66 g/cm³**	**Steel** (X2CrNiMo17-12-2) **density: 8.11 g/cm³**
94.8% aluminum 4.5% magnesium 0.7% manganes	62.81% iron 18.5% chromium 13.0% nickel 2.5% molybdenum 2.0% manganes 1.0% silicon 0.1% nitrogen 0.045% phosphor 0.03% carbon 0.015% sulfur

Table 1 – For simulation used compounds

The result in Fig.1 shows the dose rate after an irradiation time of 8 hours. In this scenario the electron beam hits a vacuum tube at a length of 1 m above a concrete floor. For the aluminum alloy the dose rate due to activation is lower by about two orders of magnitude. This simulation was repeated with a total irradiation time of 2000 hours (according to one year of operation) for different decay times. Then the activation is slightly higher (about a factor of 10), but also then the gamma dose rate for aluminum is lower than for steel by a factor of about 100.

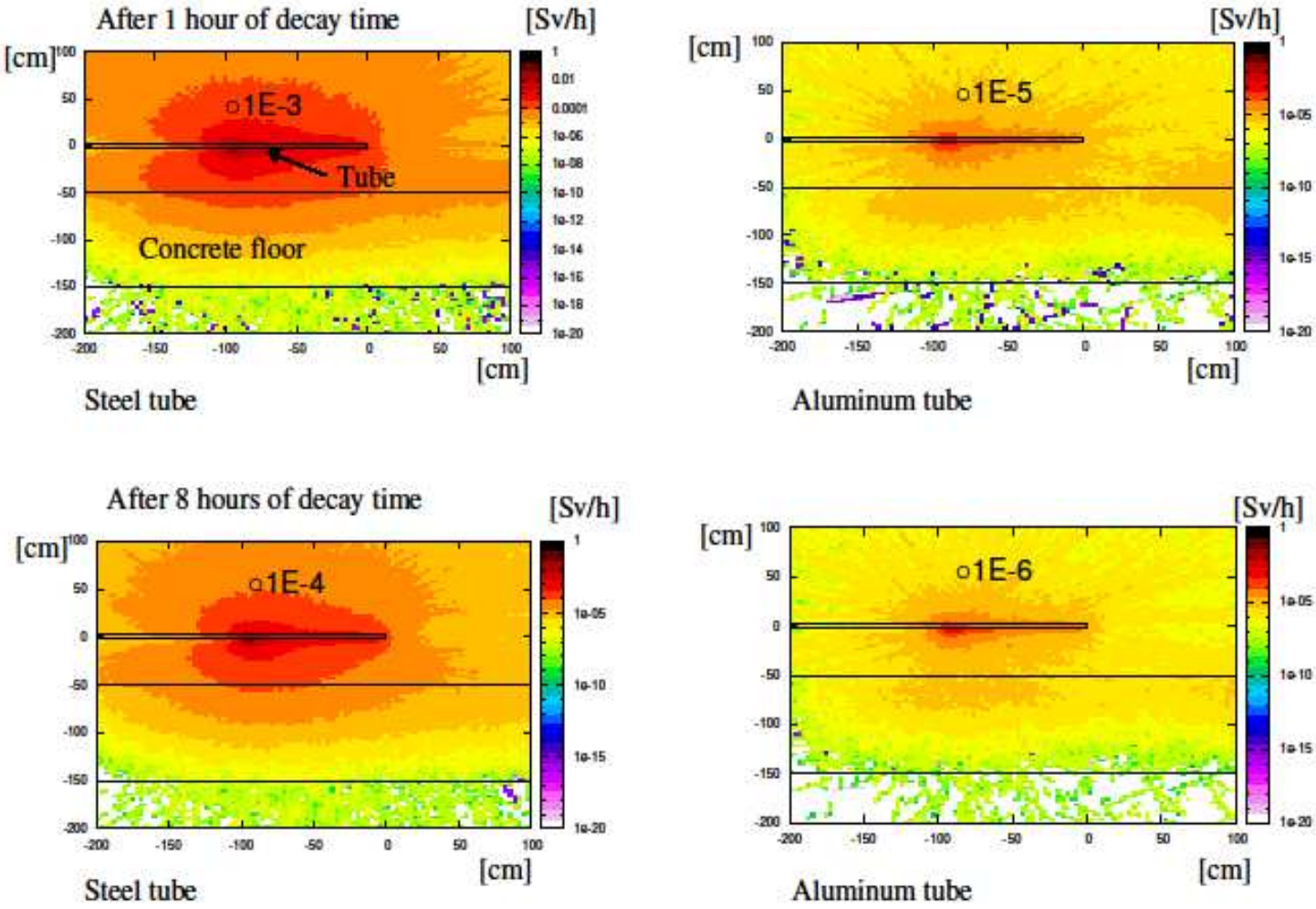


Fig.1 – Activation caused by an electron loss of 5µA/m at an electron energy of 50 MeV for a steel and an aluminum alloy

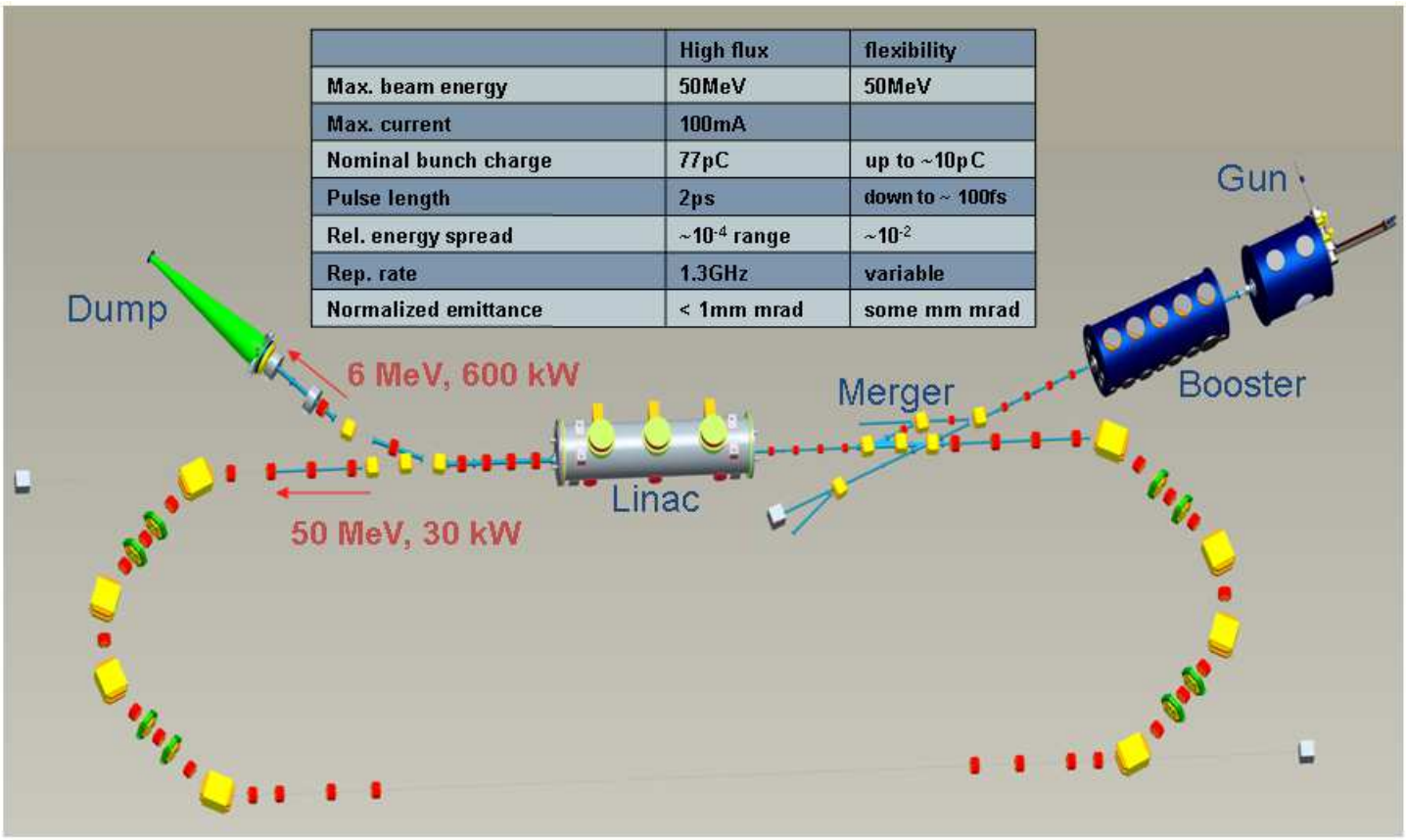
3. BERLinPro

3.1 Overview

In January 2011 the Helmholtz-Zentrum Berlin started the design of the Berlin Energy Recovery Linac Project B*ERL*inPro as a demonstrator of ERL science and technology [4] and at the beginning of 2012 the conceptual design report was finished [5]. The intention of the ERL principle is to combine the advantages of storage rings (high current, use of several beamlines simultaneously) and linear accelerators (low emittance and short bunch length).

After the electron beam is accelerated it passes the same cavity a second time but with the reverse phase. This energy is used for the acceleration of the subsequent bunches and the low energy electrons are guided to the beam dump after being decelerated in the linac module.

The machine layout and the main parameters of B*ERL*inPro are shown in Fig. 2. The beam is produced in a superconducting gun and is then accelerated to the maximum energy of 50 MeV, the maximum current is 100 mA (cw). The low energy parts of the machine (injector, beam dump line) are operated at about 6 MeV.



	High flux	flexibility
Max. beam energy	50MeV	50MeV
Max. current	100mA	
Nominal bunch charge	77pC	up to ~10pC
Pulse length	2ps	down to ~ 100fs
Rel. energy spread	~10^{-4} range	~10^{-2}
Rep. rate	1.3GHz	variable
Normalized emittance	< 1mm mrad	some mm mrad

Fig. 2 – General machine layout of BERLinPro

3.2 Consequences of activation calculations for the BERLinPro vacuum system

Dedicated assessments concerning radiation protection issues have been done so far in order to determine a detailed radiation safety concept and to obtain the construction permit in 2013. Due to the high beam power of 5 MW in the ring, 600 kW in the beam dump, the accelerator will be built subterraneously [6, 7] and a detailed modelling in Fluka of the accelerator building is in progress. Besides these studies also the activation calculations described in Sect. 2 are considered as a part of the radiation safety concept.

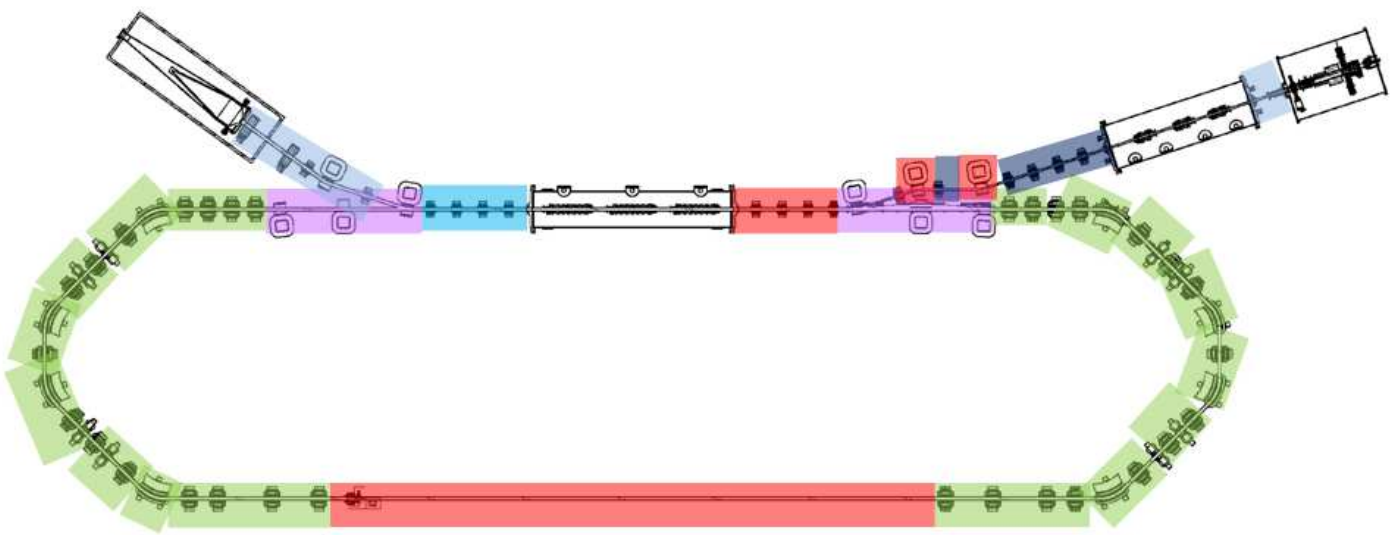


Fig.3 – Material specification for BERLinPro [8]

Color Code:

	round beam pipe Ø 70 mm Stainless Steel (1.4404)	without cooling
	round beam pipe Ø 40 mm Stainless Steel (1.4404)	without cooling
	round beam pipe Ø 40 mm Aluminum (6061 T6)	with optional cooling
	round beam pipe Ø70 mm Aluminum (6061 T6)	without cooling
	elliptic beam pipe 70 mm x 40 mm Aluminum (6061 T6)	with cooling
	rectangular beam pipe Aluminum (6061 T6)	with cooling

Fig. 3 shows the resulting combination of aluminium alloys and steel: The low energy part will be out of steel since this energy is far below the threshold for photoreactions. (E.g. for iron this threshold is at 13.8 MeV [1].) All parts which will be operated at 50 MeV are out of the aluminum alloy (compound see Tab. 1) except flanges, bellows and beam position monitors due to mechanical reasons. These components can be locally shielded. The wall thickness of the steel tubes is 2 mm and the aluminum is not thicker than 5 mm. In order to improve the vacuum conditions the aluminum tubes are NEG [1] coated.

4. Other radiation safety issues of B*ERL*inPro

Another issue concerning the simulation calculations for BERLinPro is the design of the beamdump. Because of the relatively low beam energy the penetration depth of the particles is low. Therefore the energy distribution inside the beamdump material has to be simulated in order to obtain the expected temperature profile and the optimum parameters of the incoming beam. Fig. 4 shows the resulting Fluka simulation of the energy distribution of this beamdump. The inner part is made from copper which is surrounded by steel. The incoming beam has a divergence of 150 mrad and a 2-dimensional Gaussian distribution (beamwidth. 2.5 cm) with a total current of 100 mA. Also the cooling water is implemented in this calculation. Based on these studies the construction department specified the dump (by using ANSYS) and finally it will be delivered at the end of this year [8].

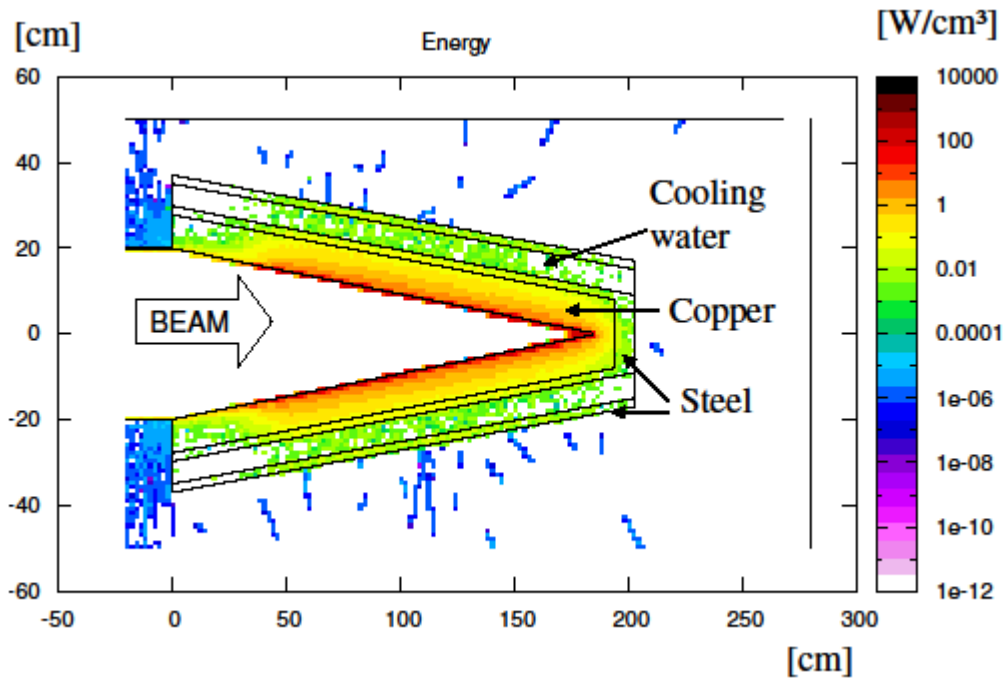


Fig.4 –- Energy distribution in the main beamdump, beamproperties: divergence: 150 mrad, 2-dimensional Gaussian distribution (beamwidth. 2.5 cm)

[1] NEG = Non Evaporale Getter

5. Summary and Outlook

It is well known that activation can be reduced by choosing proper materials. The question in the case of the design of BERLinPro is how much it can be reduced if aluminum is used instead of steel as vacuum chamber material, since a high beam power is produced. Comparing these two materials with the Monte-Carlo-Code Fluka for an electron loss of 5 μA/m at an energy of 50 MeV shows clearly that the aluminum alloy has to be preferred: The gamma dose rate caused by activation is lower by a factor of about 100 for aluminum. This leads to the decision to build the 50 MeV part of BERLinPro out of aluminum except some dedicated parts, which can be shielded locally.

This is a part of the radiation safety concept for this facility. Besides these calculations also detailed studies of the accelerator building are in progress to develop the radiation safety concept in order to obtain the construction permit in August 2013. And also first parts (e.g. the beamdump) are delivered this year. It was decided to build the machine subterraneously at the BESSYII site due to its high beam power. Furthermore an upgrade of the beam energy up to 100 MeV is an option for the future, which also has to be taken into account concerning the shielding design.

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