Radiation Protection Issues of bERLinPro

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Abstract

Energy Recovery Linacs (ERL) offer the possibility to combine the advantages of electron storage rings and free electron lasers: many beamlines that could be used simultaneously, high power beam, high spectral brilliance, high coherence, short pulses and a high flexibility in different operation modes and beam patterns. The objective of the ERL project at HZB is to demonstrate the cw linac technology with low emittance, 100 mA, and 50 MeV as a possible prototype of a next-generation synchrotron light source that is based on ERL principle [1].

Because of the tremendous beam power the facility will be placed subterraneously. The radiation in the transversal direction is three orders of magnitude lower than in the forward direction but still requires several meters of vertical shielding. Because of the long calculation times of Monte Carlo programs for thick shielding we derived analytical formulas with FLUKA [2],[3] which we used for the shielding design [4],[5]. The building work started in February 2015, the first beam of the injector is expected in 2017. We present the status of the project and details of the planning of shielding, safety measures and measurement devices. We present also results of activation calculations of groundwater, soil and air and atmospheric dispersion modeling.

1. Introduction

bERLinPro is an energy recovery linac project. The electrons are accelerated up to 6.5 MeV in the injector. They are further accelerated in the linac module of the recirculator up to 50 MeV and after one turn decelerated down to injection energy and are deflected in the dump line where they are absorbed in the main beam dump.

The energy of the decelerated electrons is used to accelerate the new injected electrons. The deceleration and acceleration processes occur simultaneously in the linac module (super conducting cavities) of the recirculator. Whether the electrons are accelerated or decelerated depends just on the phase shift of the time the electrons are inside the cavities relative to the 30 kW rf – supply.

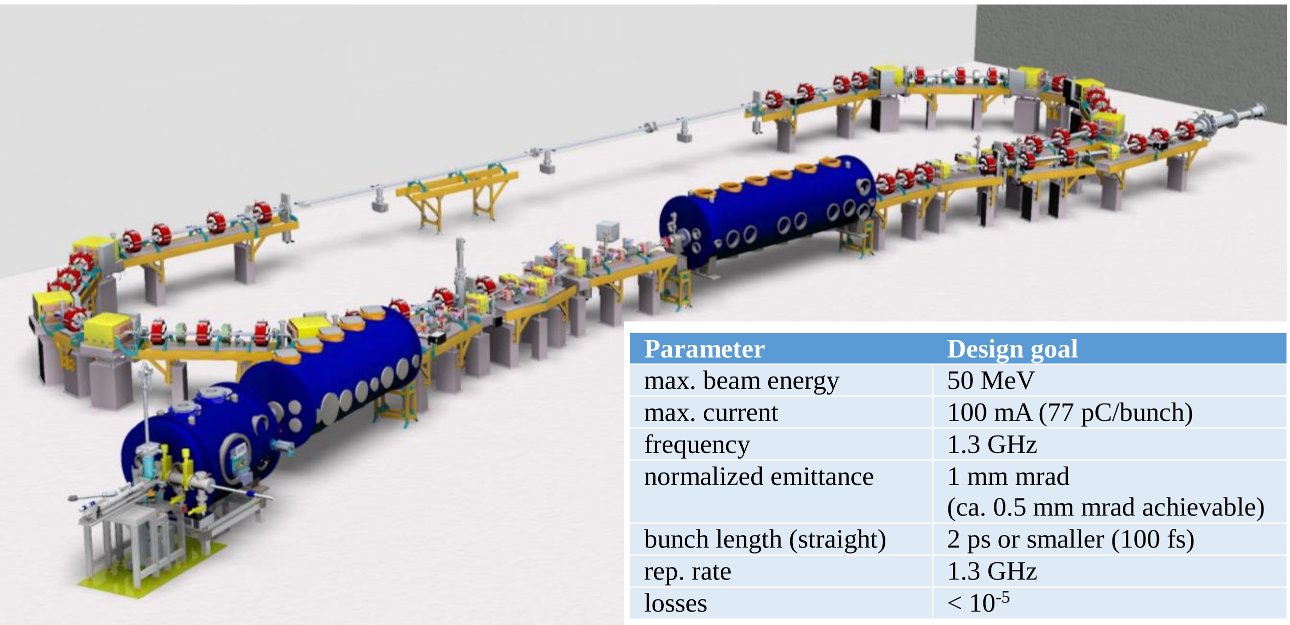
The energy recovery process makes it possible to operate the linac with much less rf – power than a standard linac would need. The 100 mA und 6.5 MeV energy after the injector means 650 kW of beam power. Without the recovery process 5 GW of rf - power would be necessary (even more, because the efficiency of the rf coupling is < 100%).

The ERL principle has two advantages in comparison with a standard linac: a) The energy of the electrons reaching the main beam dump is below the threshold energy of nuclear reactions with photons from the bremsstrahlung, so the dump line and the main beam dump (and its cooling water) cannot be activated. b) Electron losses in the recirculator are limited to the rf power supply of the linac module, in our case to 30 kW. If the losses are higher, the acceleration process immediately stops, because the accelerating energy is no longer available.

On the other hand the beam power is by orders of magnitude higher in comparison with injectors of electron storage rings of synchrotron light source. As an example, BESSYII has a full energy synchrotron that could be operated with 10 Hz and max. 1.9 GeV (typically 1.7 GeV). The maximum charge that could successfully be injected is 1 nC/shot or 10 nA or 19 W. These numbers are similar to other synchrotron light sources. Additionally the injection occurs only a couple of minutes/day. The operation of bERLinPro means a permanent injection with the maximum loss of 30 kW around the recirculator and 650 kW within the main beam dump. 30 kW corresponds to electron losses of 0.6 mA or 0.6 %. For shielding calculations we used conservatively 0.1 % losses for six point (or line) sources each around the recirculator (58 m circumference).

Typical loss scenarios at synchrotron light sources are not possible at bERLinPro e.g. mis-steered beam, because in such cases the losses are much higher than 0.6 % and a beam breakup occurs. The possible losses are mainly caused by Touschek or intra-beam scattering, interactions with rest gas molecules and therefore approximatively distributed around the recirculator.

This tremendous beam power of an ERL is by orders of magnitude higher than the injection power of synchrotron light sources. This made it necessary to reconsider methods used for the radiation safety and additionally the aspects of activation. A model of the accelerator and the most important beam parameters are shown in Figure 1.



Parameter	Design goal
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
frequency	1.3 GHz
normalized emittance	1 mm mrad (ca. 0.5 mm mrad achievable)
bunch length (straight)	2 ps or smaller (100 fs)
rep. rate	1.3 GHz
losses	$< 10^{-5}$

Fig.1 – Model of bERLinPro and machine parameters

In the following we present several new methods developed for the radiation safety of the bERlinPro project for people and environment.

2. Facility and Shielding

2.1 Overview

The accelerator will be placed subterraneously, because the bremsstrahlung in the forward direction is three orders of magnitude higher than in the transversal direction. In the transversal direction the dose rate of the bremsstrahlung is similar to the neutron radiation inside the accelerator hall. Outside the thick vertical shielding the high energy part of the neutron radiation dominates the dose rate.

The floor of the accelerator hall is positioned at -3.5 m, the vertical shielding consists of 1.4 m ordinary concrete and 3 m sand. The edge of the sand shielding is designed as slopes starting at the edges of the accelerator hall, so that the soil around the accelerator hall is also vertically shielded.

Three side walls of the accelerator hall are made of ordinary concrete. The two short side walls have a thickness of 30 cm each, and one long side wall has a thickness of 40 cm. The second long side wall is made of haematite with a thicknesses of 1.5 m (upstream of the linac module) and 1.3 m (downstream of the linac module). This wall shields the rooms next to the accelerator hall (so called “gallery”) and the walkway to the stair case, the elevator and the lifting hole. Under the walkway and under the accelerator hall is a cable duct. The “gallery” is used for technical installations, e.g. liquid He supply, that should be close to the machine, and elements of the technical infrastructure like air and water cooling and air exchange systems (underpressure of -50 Pa during operation). Also the measurement systems for activated air and cooling water are located there. From the gallery the laser tube, rf waveguides, and cryo supply lines are installed to the accelerator hall through the “balcony”, an opening in the ceiling of the accelerator hall.

All the subterraneous areas will be interlock safed exclusion areas during operation.

Above the lifting hole, elevator, stair case the technical hall is constructed at ground level. This hall houses power supplies, rf equipment, the laser for the photo cathode of the gun cavity, control system and a control room.

The accelerator hall has a height of 3 m, beam height is 1.2 m, the ceiling is 0.5 m below ground level, so the beam is 2.3 m below ground level. The ground water level on the bERLinPro site is at -1.8 m, so the beam height is 0.5 m below it. The bERLinPro accelerator hall is surrounded by a trough to keep the ground water from the subterraneous construction site. The distance between the trough and three side walls is 1.2 m. At the two short sides the trough reaches the ground level. The trough walls consist of ordinary concrete with a thickness of 60 cm and therefore improve the shielding effects of the soil and three side walls. The transversal flow of the groundwater has been investigated and found to be very slow (< 1 m/a), so activated groundwater does not contribute to indirect radiation exposure into the neighborhood of the bERLinPro site. An overview of the building configuration is given in Figure 2.

Fig2 –Overview building (courtesy of Constanze Tibes DGI Bauwerk Gesellschaft von Architekten mbH)

The progress of the building construction can be seen at:
http://www.helmholtz-berlin.de/projects/berlinpro/webcam/index_de.html

2.2 Some details of the shielding design

Outside the exclusion areas, the limits of the general public in Germany (1 mSv/a for direct radiation, 0.3 mSv/a for indirect radiation) have to be upheld. Because of the beam power, a massive vertical shielding is necessary to reach this.
At electron accelerators three main radiation contributions have to be considered: γ – radiation from bremsstrahlung, giant resonance neutrons from photons > 10 MeV, quasi deuteron fission neutrons from photons > 30 MeV and neutrons from photo – pion production, the photon energy in this case must be > 140 MeV. Analytical shielding formulas in the literature are available for electron energies much higher (e.g. > 1 GeV) than the threshold energy of the photo – pion production. The three sources of neutron production lead inside the shielding enclosure to a typical spectrum: a broad maximum at about 1 MeV and a smaller one at about 100 MeV for electron energy of 1 GeV and more. For electron energies < 1 GeV the neutron spectrum varies considerably: the spectrum ends at the electron energy, and the second maximum vanishes if the electron energy decreases. For 50 MeV electrons besides the 1 MeV maximum only a small high energetic extension is visible inside the enclosure.
There are shielding formulas available also for low energy electron accelerators (<= 50 MeV), but high power machines are not considered, so the shielding walls could be comparative thin and it is not necessary to consider high energy neutrons. As an example the preinjector of the BESSY synchrotron is a 50 MeV linac, with a charge limit of 2 nC/shot and a maximum repetition rate of 10 Hz. This corresponds to 20 nA or to the beam power of 1 W. The contribution of quasi deuteron fission neutrons to the dose from this machine is neglectable outside the 1.1 m concrete shielding of the synchrotron tunnel in which the linac is located too.

The electron energy of the bERLinPro injector as well as the dump line is 6.5 MeV and below the threshold energy of any neutron production with photons, and therefore no activations are possible in these parts of the machine. Especially for the main beam dump this is one of the major advantages of an ERL in comparison with a standard linac.
Because of the thick shielding we considered also the contributions of neutrons from quasi – deuteron fission, because high energy neutrons are much more penetrating than giant resonance neutrons. We found that the contribution of high energy neutrons determines the dose outside the thick shielding even for a 50 MeV machine. We developed shielding formulas usable for the electron energy range < 1 GeV. The details are described in two earlier papers [4],[5]. More recently we determined the attenuation coeffcients of

haematite concrete and found λ_{gn} = 35.2 g/cm² (giant resonance neutrons) and λ_{hn} 116.5 = g/cm² (high energy neutrons). Monte Carlo codes like FLUKA, which we used to develop the shielding formulas, are not useful to do the calculations for the complete thickness, because the calculations cannot be conducted in reasonable computing times. Therefore we calculated the shielding walls with our analytical formulas. Radiation through openings like cable ducts or the “balcony” we calculate of course with FLUKA. For that reason we created a FLUKA model of bERLinPro in every detail.

3. Activations

3.1 Preliminary considerations

At electron accelerators, most activations occur because of nuclear reactions with photons from the bremsstrahlung. The activation rate is given by

$$\dot{N}^{+} = \frac{\rho \cdot N_L}{A} \cdot \int_{0}^{V_0}\int_{0}^{E_0} \sigma(E_p) \cdot \Phi(E_P,\vec{r})\,dE_p\,dV \tag{1}$$

where E_p is photon energy, $\sigma(E_P)$ is cross section, $\Phi(E_P,r)$ is photon flux and ρ is density, A is mass number and N_L is Avogadro constant. The photon flux and its energy spectrum vary within the target volume. This is not known with the required accuracy to do the calculation analytically, so it is favorable to conduct the calculation of activation rates with FLUKA. The result nuclei/primary has to be multiplied with the electron loss current to get the activation rate which is also the saturation activity for this given current. The operation of accelerators is a sequence of irradiation and decay times. The resulting activation is calculated by the activation equation (2):

$$A_\nu = \dot{N}^{+} \cdot \left[1 - \exp(-\lambda \cdot t_I)\right] \cdot \exp(-\lambda \cdot t_D)\,\frac{1 - \exp(-\nu \cdot \lambda(t_I + t_D))}{1 - \exp(-\lambda(t_I + t_D))} \tag{2}$$

Where t_I and t_D are the irradiation and the decay times, $\lambda = (\ln 2)/T_{1/2}$ with $T_{1/2}$ as half life of the nucleus, ν is the number of irradiation periods, and N^+ is the saturation activity.

The calculation of the dose rate requires the knowledge of the gamma radiation constant for each decay scheme of the n produced nuclei:

$$\dot{H} = \sum_{i=1}^{n} \Gamma_i \cdot \frac{A_\nu^i}{r^2} \tag{3}$$

Instead of using eq. (3) the dose rates from activations can also be calculated directly by FLUKA. An exception are the dose rates caused by isomeric states, which we consider later.

3.2 Activations of accelerator components

The induced radioactivity of accelerator components we considered in an earlier paper [6]. As a result the decision was made that Aluminum is used for the vacuum system because the dose rates due to activations are two orders of magnitude lower than for steel.

Steel (or copper) is usable for the injector or the dump line (with the main beam dump) because the energy of the electrons at these accelerator components (and therefore the maximum energy of the bremsstrahlung) is below the threshold energy of (γ,n) reactions, so no activations of these components or the cooling water of the main beam dump are possible.

3.3 Activation of the air

Because of the high beam power the activation of the air also has to be taken in consideration. The activation of nitrogen, oxygen and carbon occurs by (γ,n) reactions each (N13, O15, C11). These nuclei are positron emitters and have short half lives (13 min, 2 min, 20 min). Be7 is produced from spallations. Two further nuclei are important: Cl39 which is produced by the nuclear reaction Ar40(γ,p)Cl39 and Ar40(n,γ)Ar41 which is produced by neutrons that are thermalized within the shielding walls. The source of

the neutrons is (γ,n) reactions of the bremsstrahlung in the vacuum system. Chlorine 39 and Argon 41 are beta emitters with half lives of 55 min and 109 min.
As with the activation calculations of the machine components, we used the maximum loss current defined by the machine protection system of 5 µA/m for the calculation of the saturation activity. (The circumference is 58 m which corresponds to 0.3 mA or 0.3 % losses).

3.3.1 Possible reduction of Ar41

Boron is used for neutron measurements, as it has a very high cross section for thermal neutrons which results in the nuclear reaction B10(n,α)Li7. In Anderson-Braun type neutron monitors the counting tube is filled with BF$_3$ gas. The α particles from those reaction are counted in the proportional counter tube. The tube is surrounded by polyethylene to moderate neutrons down to thermal energies of about 25 meV.
We considered the possibility to include Boron in the concrete enclosure of the bERLinPro bunker (walls, ceiling, floor). We wanted to see if it is possible to absorb the thermalized neutrons inside the walls to reduce the production of Ar41. Ar41 has the longest half life of the nuclei produced by air activation.
We considered several concentrations of Boron inside the concrete, also with the intention to use as little Boron as possible to reduce costs. The results for 0.5 % Boron (mass percent), the lowest concentration with a strong effect, are shown in the following.
First we show a neutron spectrum of neutrons leaving the accelerator hall through the ceiling in Figure 3.

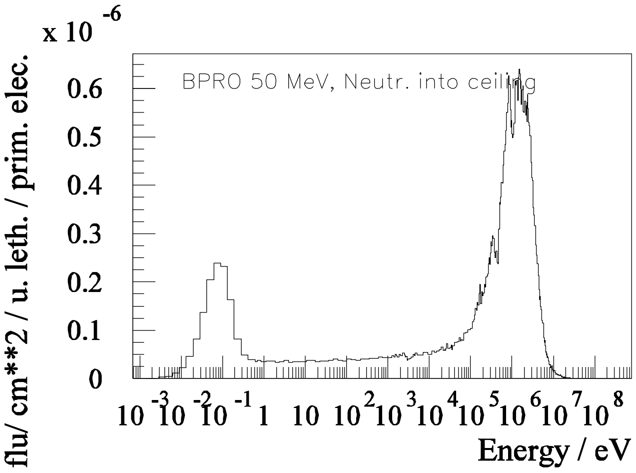


Fig.3 –Neutron spectrum of neutrons leaving the bunker (through ceiling)

The maximum on the left has an energy of 25 meV, these are neutrons that are thermalized in the concrete enclosure (and backscattered into the accelerator hall), the second maximum has an energy of about 1 MeV (giant resonance neutrons) with a small high energetic extension.
The results of the air activation calculations are given in Table 1. In the second column the values for a steel vacuum system are given. With the exception of Be7, these values are lower for the Aluminum vacuum system. Because of the lower density, less bremsstrahlung is produced in comparison with steel. With 0.5 mass % Boron in the concrete the Ar41 activation concentration is reduced considerably.

Nucleus	**Bq/m^3 Steel**	**Bq/m^3 Aluminum**	**Bq/m^3 Aluminum Colemanit**	**Bq/m^3 StrlSchV**
Be7	133	252	175	6.0E3
C11	1.22E5	8.29E4	9.06E4	3.0E4
N13	5.26E5	2.71E5	2.67E5	2.0E4
O15	6.31E5	3.81E5	3.77E5	1.0E4
Cl39	7.53E3	4.54E3	4.61E3	6.0E3
Ar41	6.69E4	1.99E4	8.22E2	2.0E3

Tab.1 –Activation concentration in accelerator hall

Boron can be added to concrete using Colemanit. Colemanit (B_2O_3+CaO+H_2O) is chemical similar to cement and is much cheaper than other substances that include Boron (especially as Boron Carbide). To include 0.5 % Boron in the floor, ceiling and walls of the accelerator hall of bERLinPro would cost only 50k€. On the other hand, in Germany the addition of Colemanit has to be certified by the Deutsches Institut fuer Betontechnologie (German institute for concrete technology), to exclude the reduction of the mechanical stability of the concrete. Therefore mechanical tests have to be done, which could be accomplished successfully. Because of the required time (about three months), the bERLinPro time line did not leave us this possibility, so we will not use Colemanit for this project.

3.3.2 Atmospheric dispersion modeling

In the right column of table 1 the limits of the German radiation protection ordinance for maximum activation concentrations of air are given. Because we exceed these limits, we will have underpressure (-50 Pa) inside the accelerator hall during operation, we have to measure the air activation, and we need a chimney to hold the limit of 0.3 mSv/a for indirect radiation in Germany. Close to BESSY a PET cyclotron is in operation which can emit 0.1 mSv/a and another institution that operates a neutron generator which can emit 0.15 mSv/a. Because of the close neighborhood, the emissions have to be added, and there are only 0.05 mSv/a left for bERLinPro. The accelerator hall is not completely dense so during operation the emission of 250 m³/h is required to hold the underpressure.
The emission occurs through our chimney with the height of 21 m, more than twice the height of the closest buildings in the neighborhood. For that reason the influence of these buildings for the air dispersion modeling do not have to be considered. Another simplification is that because of the short half lives only γ - and β – submersion have to be taken in consideration. Exposures due to radionuclei in the food chain can be excluded. The γ - submersion dose has to be calculated by the following equation [7]:

$$H_{T,\gamma,r} = A_r \cdot g_{\gamma,r,T} \cdot (\overline{\chi}^G_{\gamma 1} \cdot f_r \cdot c_{Geo,\gamma 1} + \overline{\chi}^G_{\gamma 2} \cdot (1 - f_r) \cdot c_{Geo,\gamma 2}) \qquad (4)$$

H is the annual dose in Sv/a due to submersion for the nuclide r, f is an energy spectrum factor which is 1 for the nuclei of the air activation of bERLinPro (only the first term is used), A is the annual activity for the nuclide r, g is the dose rate coefficient for the nuclide r (these values are tabulated in [7a]) , χ is the dispersion factor [7] and c_{geo} is an age factor, which is 1 for grown-ups [7a]. The height of the chimney reduces the dispersion factor χ as shown in Figure 4.

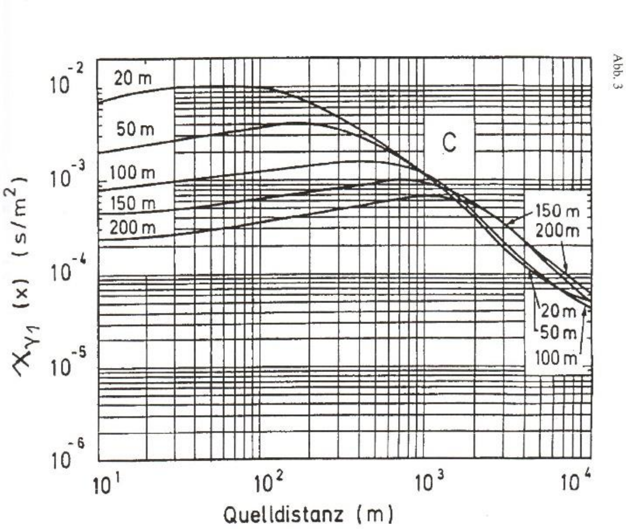


Fig.4 –Dispersion factors for γ - submersion for different heights of the chimney from [7] as function of the distance to the chimney

In our case we use the maximum of the 20 m curve with χ = 1E-2 s/m², any reduction due to the distance from the chimney is conservatively not considered. We also used the curve for diffusion category C, which results in the highest χ – value, and we used the short time dispersion factors which also results in higher values of χ than the long time dispersion factors [7]. Even with these very conservative assumptions the resulting annual dose due to γ - dispersion is only 1.26 µSv/a as shown in Table 2. But without the chimney our limit of 50 µSv/a could not be upheld.

Nuclide	g/(Sv/s)/Bq/m²)	A /(Bq/a)	H/(Sv/a)
C11	3.4E-16	4.15E10	1.41E-7
N13	3.4E-16	1.36E11	4.62E-7
O15	3.4E-16	1.91E11	6.50E-7
Ar41	4.1E-16	5.99E09	2.46E-8
Sum (Al)			**1.26 µSv/a**

Tab.2 –Annual doses by γ *- submersion*

The annual dose due to β - submersion is two orders of magnitude lower and not shown here.

We will now consider the submersion doses inside the accelerator hall directly after operation. The calculation is conducted for a person who is within a radioactive cloud (half sphere) with a radius of 10 m [7]. The γ - submersion has to be calculated using the following formula [7]

$$H_{T,\gamma,r} = C_r \cdot g_{\gamma,r,T} \tag{5}$$

C_r is the activation concentration, g is the dose rate coefficient for γ - submersion (these values are tabulated in [7a]). The results are given in Table 3.

Nuclide	g/(Sv/s)/Bq/m³)	C /(Bq/m³)	H/(Sv/h)
C11	2.4E-15	8.29E04	7.17E-7
N13	2.4E-15	2.71E05	2.34E-6
O15	2.4E-15	3.81E05	3.29E-6
Ar41	2.9E-15	1.99E04	1.77E-8
Sum (Al)			**6.36 µSv/h**

Tab.3 –Dose rates by γ *- submersion in the accelerator hall*

The same calculation for a vacuum system of steel results in a dose rate of 11.2 µSv/h.

Because of the short distance in the cloud the β - submersion is also considered. We use again eq. (5) for the calculation [7] with the different dose rate coefficients g for β - submersion of the skin [7a]. The results are summarized in Table 4.

Nuclide	g/(Sv/s)/Bq/m³) (skin)	C /(Bq/m³)	H/(Sv/h) (skin)
C11	2.2E-14	8.29E04	6.56E-6
N13	2.9E-14	2.71E05	2.83E-5
O15	4.5E-14	3.81E05	6.17E-5
Ar41	2.7E-14	1.99E04	1.93E-6
Sum (Al)		0.98 µSv/h (whole body)	**98.5 µSv/h (skin)**

Tab.4 –Dose rates by β *- submersion in the accelerator hall*

From the β - submersion dose of the skin we calculated the doses for the whole body in table 3 using the weighting factor of skin 0.01 of the German radiation protection ordinance. The same calculations for a steel vacuum system result in 1.73 µSv/h (whole body).

4. Activation of soil

4.1 Calculation of radio nucleii

The activation of soil occurs by the absorption of bremsstrahlung due to electron losses in the forward direction.

We calculated the bremsstrahlung for an angle of 1 mrad, 0.1 % losses (100µA, 50 MeV), and an aluminum vacuum tube see Figure 5. We used also magnetic fields in the dipole chambers, which causes also electron losses and resulting bremsstrahlung around the arc. In our scenario we divided the 120 cm soil between concrete wall (30 m concrete) and trough wall (60 cm concrete) in 12 layers. One layer is 10 cm thick, has a height of 3 m (inner height of accelerator hall) and a width of 7.1 m which is the distance from the center of the machine to the outer side wall.

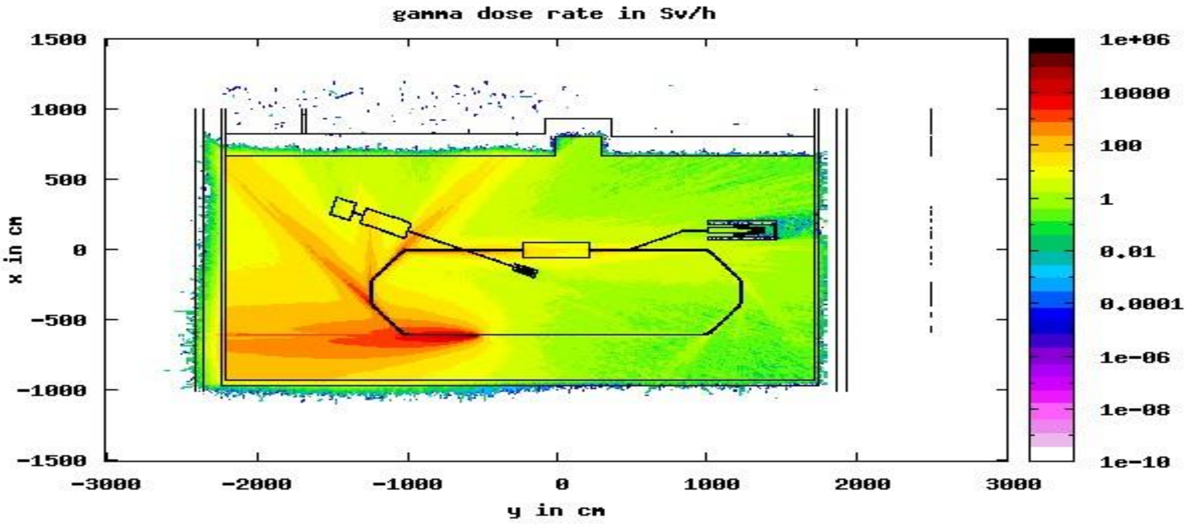


Fig. 5 – Gamma Dose Rate in Sv/h 0.1 % losses (100 µA, 50 MeV).

The beam height is lower than the groundwater level, so we used the wet soil composition of DESY [8] for our calculations. The soil in Hamburg and Berlin is very similar, consisting predominantly of sand.

4.2 Activation of soil

The bremsstrahlung from electron losses along a long side of the recirculator hits the concrete wall and the soil behind. We calculated the number of nuclei/primary in the soil volume between the concrete wall and the trough with FLUKA, and in a second step we calculate the activity with the activation equation:

$$A_\nu = \dot{N}^+ \cdot \left[1-\exp(-\lambda \cdot t_I)\right] \cdot \exp(-\lambda \cdot t_D) \frac{1-\exp(-\nu \cdot \lambda (t_I + t_D))}{1-\exp(-\lambda (t_I + t_D))} \qquad (6)$$

t_I and t_D are the irradiation and the decay times, $\lambda = (\ln 2)/T_{1/2}$ with $T_{1/2}$ as half life of the nucleus, ν is the number of irradiation periods, and N^+ is the saturation activity or the maximum possible activation rate for a given nucleus and a given current. It is calculated with FLUKA and the loss current. If we consider an irradiation pattern 8 h on, 16 h off, at 365 d we calculated the activities within first layer of 10 cm soil. The results are given in Table 5.

In Table 5 the nuclei with longer half lives (several months or years) are printed with bold letters. In the last column the limits for the unrestricted release of soil according to the German radiation protection ordinance are given. Save Ca47 with its short half life of 4.54 d only Na22 and Mn54 exceed this limit (the relative exceeding value for both nuclei is 25.1, the limit is 1). In the last layer of the soil between the accelerator hall and trough no activation concentration is above these limits and the sum of the relative exceeding values for all nuclei is < 1.

Nuclide	**Half life**	**Activity / Bq**	**Spec. Activity Bq/g**	**Spec. Act. Limit Bq/g**
He3	**12 a**	**3.81E6**	**1.01**	**60**
Be7	53 d	1.95E7	5.17	30
C14	**5700 a**	**2.15E4**	**5.6E-3**	**10**
Na22	**2.6 a**	**5.60E6**	**1.48**	**0.1**
Na24	14.96 h	7.16E6	1.9	-
Si31	2.62 h	5.65E5	0.15	-
Ar37	35 d	2.80E7	7.42	-
Ar39	**269 a**	**2.98E3**	**7.9E-4**	**-**
K42	12.36 h	3.77E5	0.1	0.8
K43	22.2 h	6.63E5	0.18	0.2
Ca45	163 d	6.56E6	1.74	400
Ca47	4.54 d	2.25E6	0.59	0.2
Cr51	27.7 d	4.44E6	1.17	8
Mn52	2.58 h	1.60E6	0.43	0.2
Mn54	**312.2 d**	**1.18E7**	**3.1**	**0.3**
Mn56	2.58 h	3.13E4	8.2E-3	0.1
Fe52	8.27 h	8.52E4	0.023	0.7
Fe55	**2.73 a**	**1.43E8**	**37.9**	**200**
Fe59	44.5 d	7.25E5	0.19	0.2

Tab.5 – Activities within the first layer of soil for 0.1 % losses (100 µA, 50 MeV).

4.3 Illumination of soil

From our calculations we found also several nuclei that are non-radioactive, but they are products of nuclear reactions and as such in an excited state, different from the ground state by the nuclear spin. The half life of isomeric states is typically in the nsec - µsec range, and the energy between the isomeric states and the respective ground state has a mean value of about 1 MeV. During operation of the accelerator, these states are in radiation equilibrium with the bremsstrahlung. If the accelerator is switched off, there is no dose contribution by these because of their short half lifes.

The emission of photons from the isomeric states occurs isotropically. Because the soil volume considered is covered by a sloped sand layer, the additional dose contribution in the vertical direction should be considered. There are myriads of isomeric states possible, and the dose contributions by them are not included in FLUKA. On the other hand the activity of the non – radioactive nuclei is calculable with FLUKA (and the loss current) using the same method described before. In the activation equation we consider only one irradiation period of 8 h and no decay time, all activities are saturated. The results are summarized in Table 6.

Nuclei with stable groundstate	**Activity / Bq**
D2	6.98E11
He4	2.54E10
C12	4.77E9
N14	1.01E9
N15	3.79E9
Mg24	1.84E9
Mg26	1.13E9
Al27	5.19E9
Si28	9.11E8
Si29	7.33E8
K39	1.06E9

Tab.6 – Activities of short living isomeric states within the first layer of soil for 0.1 % losses (100 µA, 50 MeV).

The gamma radiation constant is given by

$$\Gamma = \frac{1}{U_I} \cdot \frac{\sum_{i=1}^{n} (\eta/\rho)_i \cdot w_i \cdot E_i}{O \cdot t} \cdot \frac{r^2}{A} \tag{7}$$

where U_I = 33.7 V is the ionization constant of the air, n is number of emitted photons /decay, $(\eta/\rho)_i$ is mass energy absorption coefficient of air for the given photon energy, w_i is emission probability of the given photon, E_i is energy of the photon, O = $4\pi r^2$ the surface of a sphere around the radiation source, t the emission time, r is the distance and A the activity.

Because we do not know which nuclear spins the isomeric states really have and how they reach their ground state, we assume that one photon/nucleus of 1 MeV is emitted. For the gamma radiation constant we get with (η/ρ) = 0.0278 cm^2/g for air and the photon energy E = 1 MeV, n=1, A=1 Bq, r=1 m, O=4π m^2, t =1 sec

$$\Gamma = 1.467 \cdot 10^{-13} \ \frac{Sv \cdot m^2}{h \cdot Bq} \tag{8}$$

The dose rate is then given by

$$\dot{H} = \Gamma \cdot \frac{A}{r^2} \tag{9}$$

The total activity for the isomeric states is 7.44E11 Bq. From eq. (9) we get the dose rate of 0.11 Sv/h in 1 m distance. The vertical distance to the surface is 230 cm. If we consider the area of S = 0.2 m^2, that is the area a person needs to stand, on a sphere with the radius of 2.3 m we get the solid angle Ω = S/r^2 = 0.038 sr. To include the effect of isotropic radiation we multiply eq. (9) by the factor Ω/4π = 3E–3.

The mass energy absorption coefficient for wet soil [8] we calculated from the elements of the mixture with (η/ρ) = 0.0283 cm^2/g, or with ρ= 1.8 g/cm^3 we have η = 0.051 cm^{-1}. Altogether we have

$$\dot{H} = \frac{\Omega}{4\pi} \cdot \Gamma \cdot \frac{A}{r^2} \cdot \exp(-\eta \cdot r \cdot 100) \tag{10}$$

With r = 2.3 m we get from eq. (10) a dose rate of 2.65 nSv/h at the ground level. This is still conservative, because this part is covered by the sloped sand layer. We come to the conclusion that the illumination of soil in the case of bERLinPro is no problem for the dose at the surface of the vertical shielding. For subterraneous installations of accelerators in general this additional contribution to the vertical dose should be considered carefully.

5. Monitoring and technical radiation safety measures

The ambient dose measurement system will consist of six stations (one ionization chamber and one neutron monitor each) above the accelerator hall and two in the gallery. The neutron monitors will be supplied with lead moderators developed by us (Deutsches Gebrauchsmuster DE20 2013 011 938 U11 (2014)), so they can measure also neutrons > 10 MeV (up to 1 GeV). Two air measurement systems will be installed, one in the tube to the chimney, which measures the outgoing air during operation. If the operation of the accelerator is stopped, the access to the accelerator hall is not immediate possible. The access depends on the values of the air activation and the dose rates due to activation of accelerator components measured by a stationary gamma counter inside the accelerator hall. If both values are below a given limit, access to the accelerator hall is possible. The entrance door is controlled by the personal interlock.

If the air activation is below the limit, the air of the accelerator hall can be exchanged. This will be done with an air renewal rate of 6 per hour. The outgoing air of the air exchange system will be measured by the second air measurement system and leaves the facility by a large chimney with the height of the technical hall.

During operation the air is cooled in a closed air cooling system. This system is located in the gallery. The system of water cooling is also located there; it is a closed circuit. If a water leakage occurs in the accelerator hall or in the gallery, the water is collected in a reservoir in which its activation will be measured. If it is declined below the limit it will be given in the public waste water system.

6. Outlook

The construction of the building is in progress, the completion of the building shells of the accelerator hall is expected at the beginning of 2016, of the technical hall in June 2016. The technical infrastructure of the building will be accomplished in 2016. The installation of the accelerator components will start in 2016. The operation of bERLinPro will be conducted in four stages: test of the guncavity with photocathode (KCsSb) 5 µA and E< 4 MeV in 2016 within the HoBiCaT bunker, rf tests of the superconducting cavities in 2017 within the accelerator hall, operation of injector and dump line (max energy 6.5 MeV) in 2017, operation of the recirculator in 2019 (I < 10 mA) and with maximum beam of 100 mA in 2020.

7. Summary

bERLinPro is a test facility and an accelerator experiment to demonstrate and develop new accelerator technology. The high beam current is seven orders of magnitude higher than a typical beam current injected into a storage ring of a synchrotron light source at 10 Hz. New methods have to be developed for the radiation safety for such an accelerator. Because of the high beam power the facility will be placed subterraneously, for economic reasons, because the radiation in forward direction is three orders of magnitude higher than in transversal direction. A thick vertical shielding is needed though. This made it necessary to develop new analytical shielding formulas for a low energy electron accelerator whose beam power is that high, that high energy neutrons determine the dose outside the thick shielding. A lead moderator has been developed, that enables standard neutron monitors to extend the measurement range from 10 MeV to 1 GeV (Deutsches Gebrauchsmuster DE20 2013 011 938 U11 (2014)). These monitors will be used to measure the ambient neutron dose outside the vertical shielding. The activation of accelerator components has been calculated with FLUKA. As result, the material aluminum will be used for the vacuum system of the recirculator instead of steel. The activation of air has been calculated by FLUKA, the results have been used to develop the concept for the measurement and the handling of the outgoing air. With the atmospheric dispersion modeling it was shown, that the chimney is sufficient to hold the limit for indirect radiation. It was calculated, that an addition of 0.5 % Boron (using Colemanit) to the concrete is sufficient to reduce the Ar41 production by one to two orders of magnitude. The transversal velocity of the ground water is neglectable, so an exposure by activated ground water is not possible. It was found from calculations of earth activations, that the activation concentration limit for unrestricted release of the earth is hold outside the trough. Doses by earth activation during operation are higher due to the contribution of isomeric states, but it was shown that the vertical shielding is sufficient to hold the limit for direct radiation outside the shielding. To determine shielding details like cable ducts and labyrinths for media supply a detailed FLUKA model of bERLinPro has been developed.

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