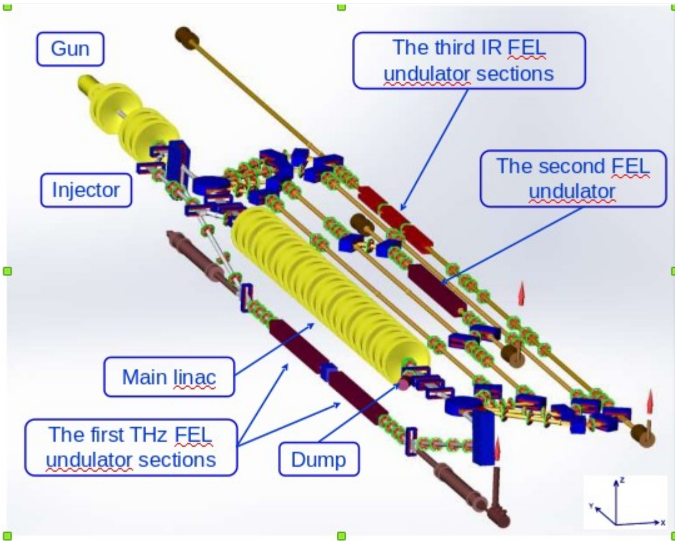
Estimates and measurements of photon and neutron radiation doses of microtron-recuperator of Novosibirsk FEL

T.V. Salikova, N.A. Vinokurov, V.A. Repkov, N.S. Shamakina

Institute of Nuclear Physics G.I. Budker SB RAS, avenue ac. Lavrentieva 11, Novosibirsk, Russia, 630090

T.V.Salikova@inp.nsk.su

The work provides estimates and measurements of the dose rate of photon and neutron radiation in the accelerator hall of FEL. The kinetic energy of electrons varies from 12 to 40 MeV, this is the region of the giant dipole resonance. The birth of photoneutrons and the activation of the technical elements of the microtron-recuperator take place. Measurements and calculations allow us to estimate the levels of induced radioactivity and the times of degradation of materials (products) under the influence of radiation.



The Novosibirsk FEL of the terahertz and far-IR ranges is designed to generate narrow spectral lines with smooth continuous tuning of wavelengths from 5 to 240 μm [1]. FEL is created based on the 40 MeV accelerator-recuperator.

1st stage of the FEL - one vertical track on which the undulator is installed.
2nd stage of the FEL - two horizontal tracks, on the bypass of the second track installed undulator.
3rd stage of the FEL - four horizontal tracks, on the fourth track installed undulator.

The physical parameters of the accelerator-recuperator and the FEL

	1st FEL	2nd FEL	3rd FEL
Number of tracks	1	2	4
The kinetic energy of the electrons [MeV]	12	20	40
Electron beam current I [mA]	10	10	3.5
The repetition rate of electron bunches [MGz]	5.64	7.52	3.75
The wavelength of FEL radiation [μm]	90÷240	40÷80	5÷20
The average power of FEL radiation [W]	500	100÷500	30÷10 kW
The peak power of the FEL radiation [MW]	0.5	2	10
Line width (as a percentage)	0.3÷1	0.2÷1	0.1÷1

The grouped electron bunches in the accelerating phase pass through the sixteen RF resonators of the accelerator-recuperator, then enter the undulator, where they lose approximately 1% of their energy to terahertz radiation. Then the spent electrons in the braking phase pass through the RF resonators, slow down to the injection energy and enter the dump.

The structure of the FEL: injector, one vertical and four horizontal paths of the accelerator-recuperator, which have a common accelerating RF system of sixteen resonators, a copper 100 kW beam dump.

The injector consists of 268 kV electron gun and three RF resonators. The injector generates grouped electron bunches with a kinetic energy of 1.5 MeV. The average current of the beam varies from 30 mkA to 10 mA, by changing the frequency of clots from 22 kHz to 11.2 MHz.

The current losses of the beam are determined by the current sensors installed at the check points: the first sensor is installed at the output of the beam from the gun (268 keV); the second — at the output of the injector (1.5 MeV); the third sensor measures the current of the beam that got into the copper dump (1.5 MeV). In the mode of generating terahertz radiation, the total current losses on all tracks of the microtron-recuperator are in the range from 0.1 to 0.3 mA.

calculations of the dose rate of bremsstrahlung in the accelerator hall

The locations of beam losses can be determined by the readings of temperature sensors (installed along the vacuum chamber), vacuum deterioration (the control current of the magnetic discharge pump), and an increase in the radiation level (Geiger counters and ionization chambers installed on the vacuum chamber). The likely points are bending magnets, copper collimators, and areas behind undulators (Fig. 1). neither the angle of incidence of electrons on the target nor the thickness of the target is known, so the calculations use the recommendations for estimating the dose rate from the IAEA report No. 1. 188 [2], SanPiN 2.6.1.2573-10 [3] and the optimal target thickness [4] (at which the maximum output of bremsstrahlung is achieved).

$\dot{D}_{(R,I)}=\dfrac{\dot{D}_{1(\theta)}\cdot I}{K\cdot R^2}$	$\dot{D}_{(R,I)}$	the dose rate of bremsstrahlung at the calculated point behind the protective screen.
	R	distance from the radiation source to the calculated point, in meters.
	K	multiplicity of dose attenuation by protection elements.
	I	the beam current in a mA.
	$\dot{D}_{1(\theta)}$	dose rate (Gy·m²/h) at a distance of 1 meter from the radiation source at an angle θ (in degrees) to the direction of electron movement, the beam current is 1 mA.
	θ	the angle between the beam direction and the calculated point, in degrees.
	E_e	kinetic energy of electrons in MeV.

The dose rate of bremsstrahlung at a distance of 1 m from the target (at an angle of $\theta=0^0$) can be calculated using the empirical formula given in the IAEA report no. 188 [2, p. 53]:

E_e < 20 MeV	$\dot{D}_1=20\cdot E_e^2$ Gy·m²/(kW·h) $\dot{D}_1(I)=20\cdot E_e^3\cdot I$ Gy·m²/h
20 ≤ E_e < 100 MeV	$\dot{D}_1=300\cdot E_e$ Gy·m²/(kW·h) $\dot{D}_1(I)=300\cdot E_e^2\cdot I$ Gy·m²/h

Contribution to the dose rate (in kGy/h) of photon radiation at a distance of one meter from the point of loss of part of the beam (δI in mA) in some parts of the accelerator. In the mode of generating terahertz radiation, the total current losses on all tracks of the microtron-recuperator are in the range from 0.1 to 0.3 mA.

	E_e	δI	$\dot{D}_1$
In injector	1.5	1	0.0675
In dump	1.5	10	0.675

1st FEL

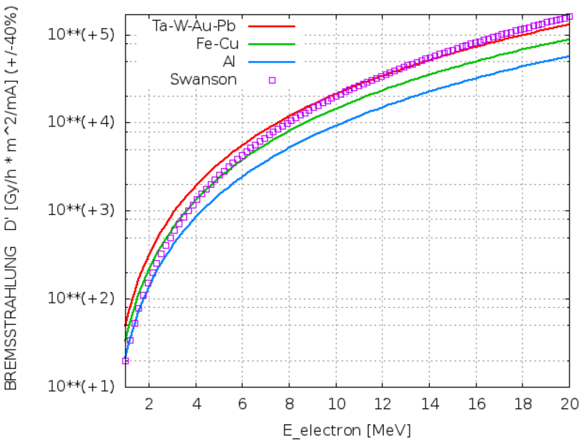
E_e MeV	$\dot{D}_1$ δI=0.03 mA	$\dot{D}_1$ δI=0.1÷0.3 mA	$\dot{D}_1$ δI=1 mA
10	0.6	2÷6	20
12	1.04	1÷10.4	34.56
15	2.025	6.75÷20.25	67.5

2nd and 3rd FEL

Track number	E_e MeV	$\dot{D}_1$ δI=0.03 мА	$\dot{D}_1$ δI=0.1÷0.3 мА	$\dot{D}_1$ δI=1 мА
1	10	0.6	2÷46	20
1	12	1.04	1÷10.4	34.6
2	20	3.6	12÷36	120
2	22	4.36	14.52÷43.56	145.2
3	30	8.1	27÷81	270
3	32	9.2	30.7÷92.16	307.2
4	40	14.4	48÷144	480
4	42	5.3	52.92÷158.8	529.2

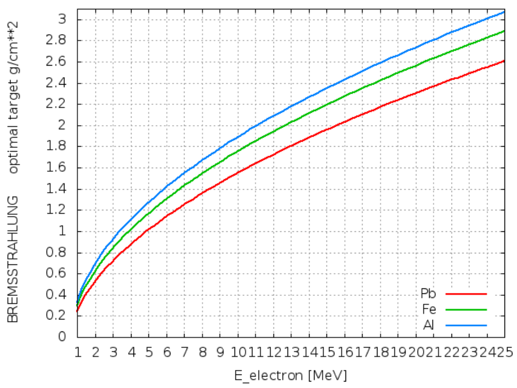
Let's compare the data obtained with the results obtained using the formulas given in the work of V. I. Tsovbun [4]. The output of radiation from copper (iron) target is 1.56 times higher than from aluminum, but 1.54 times lower than from a lead. *Estimates of dose rates may differ by 2.5 times depending on Z.*

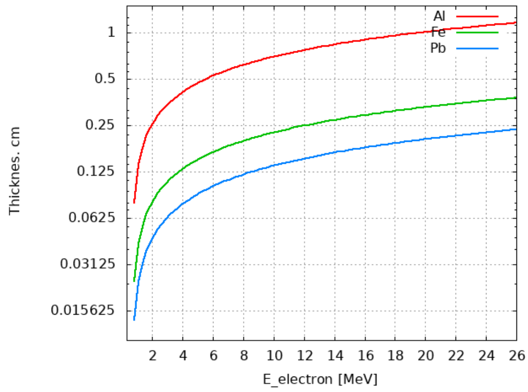
target	
^{73}Ta - ^{74}W - ^{78}Au - ^{82}P	$\dot{D} = 51.6 \cdot E_e^{2.63} \cdot I$
^{26}Fe – ^{29}Cu	$\dot{D} = 33.6 \cdot E_e^{2.63} \cdot I$
^{13}Al	$\dot{D} = 21.6 \cdot E_e^{2.63} \cdot I$



The dose rate also depends on the thickness of the target. The "optimal thickness" (t in g/cm^2) of the target provides the maximum output of bremsstrahlung (the formula is applicable up to 25 MeV):

$$t\left[g/cm^2\right] = 0.89 \cdot (E_e - 0.7) \cdot Z^{-0.17 \cdot E_e^{-0.2}}$$





calculation of the neutron radiation dose rate in the accelerator hall

Calculation of the **neutron radiation dose rate** at the check point behind the protective screen using the formula from SanPiN 2.6.1.2573-10 [9 p. 29]:

$$\dot{Д}_{(R,I)} = \frac{6.25 \cdot 10^{15} \cdot f \cdot I \cdot \alpha}{4\pi \cdot R^2 \cdot K} = \frac{5 \cdot 10^{10} \cdot f \cdot I \cdot \alpha}{R^2 \cdot K} \ \mu Gy/h$$

$$\dot{Д}_{(R,I)} = \frac{12.68 \cdot I \cdot E_e}{R^2 \cdot K} \ Gy/h$$

Conversion coefficient of neutron flux density to dose rate:

α=1.7·(μGy·cm^2·s)/h.

Photoneutron yield coefficient per electron:

$f = 1.5 \cdot 10^{-4} \cdot E_e$

Starting from the energies of 6÷10 MeV, photon absorption causes photonuclear reactions (the region of the giant dipole resonance of 6÷100 MeV). In this energy region is the energy spectrum of the bremsstrahlung of the accelerator-recuperator.

Contribution to the dose rate of neutron radiation at a distance of 1 meter from the point of loss of part of the beam δI on the tracks of the microtron-recuperator.

E_e [MeV]	$\dot{Д}_1$ [Gy/h] δI=0.03 mA	$\dot{Д}_1$ [Gy/h] δI=0.1÷0.3 mA	$\dot{Д}_{1\ max}$ [Gy/h] δI=1 mA
10	3.8	12.7 ÷ 38	126.8
12	4.6	15.2 ÷ 45.6	152.2
15	5.7	19 ÷ 57	190.2
20	7.6	25.4 ÷ 76.1	253.6
30	11.4	38 ÷ 114	380.4
40	15.2	50.7 ÷ 152.2	507.2
45	17.1	57.1 ÷ 171.2	570.6

The IAEA report 188 [2] provides a formula for neutron yield for 1 kW electron beams from semi-infinite targets with different Z

$$Y = 9.3 \cdot 10^{10} Z^{(0.73 \pm 0.05)} \frac{нейтронов}{сек \cdot кВт}$$

$$\dot{Д}_1 \approx 1.7 \cdot 10^{-10} \cdot Y \cdot \delta I$$

The dose rate (Gy/h) of neutron radiation at a distance of 1 meter from the loss point. Current losses δI are measured in mA.

	10^{10} neutron/(s·kW)	$\dot{Д}_1$ [Gy/h] dI=1 1mA
$_{13}Al$	60.5÷68.8	116
$_{26}Fe$	100.3÷118	200
$_{29}Cu$	100.8÷128.6	218
$_{82}Pb$	232÷289	490

The dose rate of neutron radiation from a copper (iron) target is twice as high as from an aluminum target.

Comparison of measured and calculated doses at control points

The dose at the check point can be estimated as the sum of doses $\sum_{(R,Z,\rho)} D_{(E_e,\delta I,R,\theta,Z,\rho)}$ from several targets located at a distance R at an angle θ, and the sum of reflected radiation (albedo) $\sum_{(R,concrete)} Albedo_{(E_e,\delta I,R,\theta,concrete)}$ from the concrete walls of the accelerator hall.

$$\sum_{(R,Z,\rho)} D_{(E_e,\delta I,R,\theta,Z,\rho)} + \sum_{(R,Z,\rho)} Albedo_{(E_e,\delta I,R,\theta,Z,\rho)}$$

The distance between geodesic axles of 6 m, the height of the ground floor is 3.6 m.
Distance from the floor to the median plane of the horizontal tracks of accelerator 2.6 m.
Thick concrete walls 3 meters. Four thermoluminescent ДВГН-02 sensors in polyethylene retarders are installed along the axis number 7, at a distance of 1 meter above the median plane. One sensor is installed between the 5 and 6 axes in front of the transport gate.

Dimensions of the accelerator hall: length 48.8 m, width 6 m, height 7.8 m. The volume of the hall is 2300 m^3.

2 FEL. E_e=20 MeV.

	Measured dose rate		Calculated dose rate	
Control point	$\dot{D}_{(R)}$ [mGy/h]	$\dot{Д}_{(R)}$ [mGy/h]	$\dot{D}_{(R)}$ [mGy/h]	$\dot{Д}_{(R)}$ [mGy/h]
Northern wall	32.2; 152 (91.4)	6.9; 62	10÷300	6÷100
Middle of the hall	105.2; 362.6 (408)	98.5; 70.3;	20÷ 800	6÷150
Southern wall	21.8; 132 (95)	11; 27.8	0.5÷100	6÷70
In front of gate №2 (South)	1.75	0.565	0.1÷50	<2

3 FEL. E_e=40 MeV.

	Measured dose rate		Calculated dose rate	
Control point	$\dot{D}_{(R)}$ [mGy/h]	$\dot{Д}_{(R)}$ [mGy/h]	$\dot{D}_{(R)}$ [mGy/h]	$\dot{Д}_{(R)}$ [mGy/h]
Northern wall	291	212	30÷1000	10÷300
Middle of the hall	605	696	50÷3000	10÷500
Southern wall	350	315	1÷500	10÷250

At work 2 FEL, the measured dose rates coincide with the calculated ones. A significant difference between the measured doses and the calculated when working with 3 FEL. This is determined by the uncertainty of the location of the current loss site and the magnitude of the loss at electron energies in the range of 10, 20, 30, and 40 MeV.

The work was done at the shared research center SSTRC on the basis of the Novosibirsk FEL at BINP SB RAS, using equipment supported by project RFMEFI62119X0022.

Reference

1. O. A. Shevchenko, N. A. Vinokurov, etc. "Novosibirsk laser on free electrons." Izvestiya RAS. Series physical, 2019, volume 83, No 2, pages 278-281.

2. W. P. Swanson. “Radiological safety aspects of the operation of electron linear accelerators”. IAEA, Vienna, 1979.

3. Hygienic requirements for the placement and operation of electron accelerators with energy up to 100 MeV. SanPiN 2.6.1.2573-10. Moscow, Federal center for hygiene and epidemiology of Rospotrebnadzor, 2010.

4. V. I. Tsovbun. "Electronic accelerators with an energy of 0.5-100 MeV as radiation sources". JINR 16-7104. Dubna 1973.