

The Powerful Nanosecond Duration Electron Beam Effect on the Crystalline Tungsten Target

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Sinus-7 Electron Source Layout



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2m

One of the possible methods of obtaining monochromatic X-ray radiation short “flashes” is parametric X-ray radiation (PXR) generated by the nanosecond duration electron beam. For this purpose the powerful electron beam effect on the tungsten crystalline target has been investigated experimentally. The accelerator of the direct effect “Sinus-7” has been used as an electron source, where the electron beam is formed in the flat vacuum diode in the magnetic field. The accelerating pulse duration is 50 ns, the electron energy is 1.1 MeV, the current density on the target surface is $\sim 250 \text{ A/cm}^2$, pulse duration frequency is 1-100 Hz. In this type of accelerators electrons are emitted from plasma arising on the cathode surface, that allows electron flows with the particle density of 10^{14} - 10^{17} cm^{-3} to be formed.

Primary Electron Beam Parameters

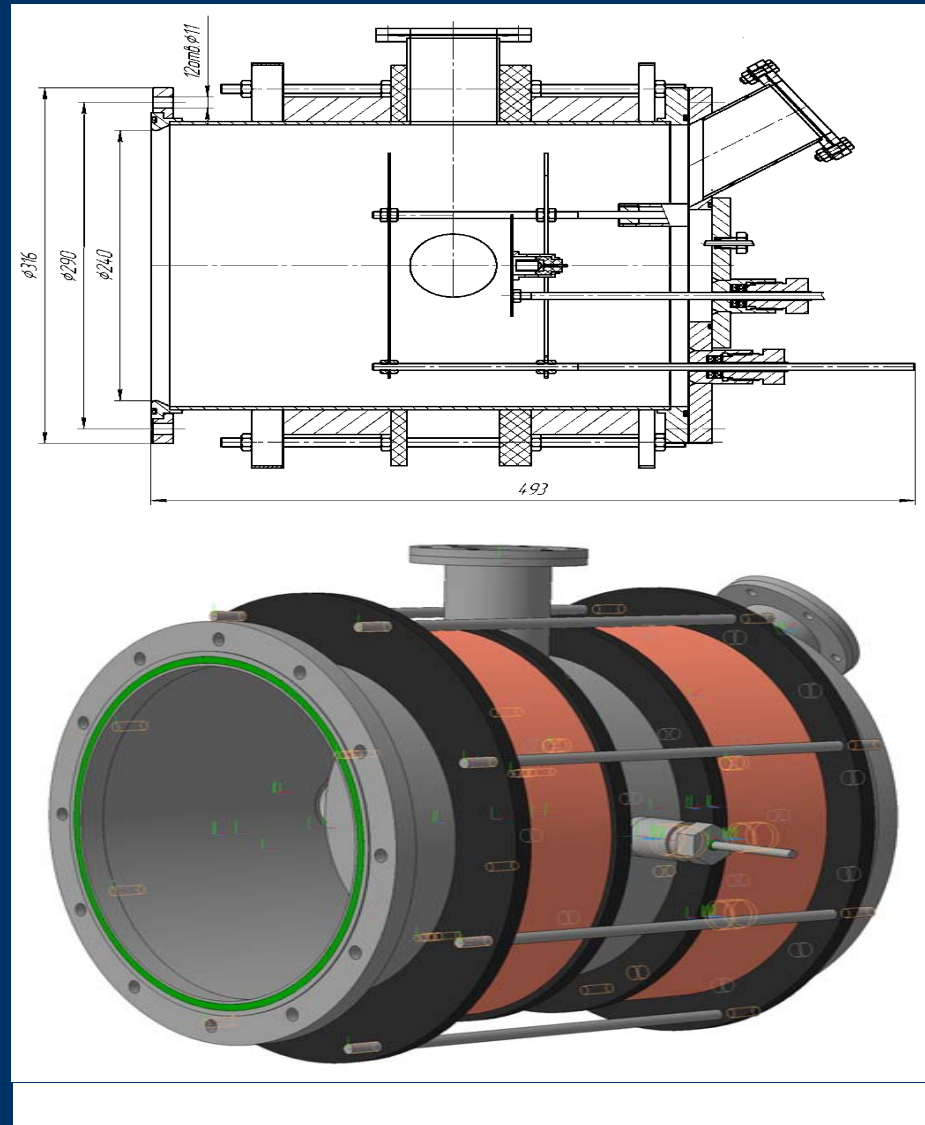
- Energy – 1,1MeV
- Bunch Duration – 50 ns
- Maximal beam rate – 100 Hz
- Bunch charge – $7.8 \times 10^{13} e^-$

Photon production efficiencies for the first(second) bunch:

- Crystalline 0.5- mm-thick tungsten target
- Diameter 12 mm

The tungsten monocrystal of the diameter of 12 mm, of the length of 0.5 mm, the normal to the surface of which has coincided with the direction [111], has been used as a target. The crystal surface disorientation with the plane (111) has been 20 angular minutes. The investigation of the quality and mosaicity of the tungsten target W(111) on the crystal-diffractometer has shown that the “rocking curve” full width at the half-height maximum $\text{FWHM} = 0.14260$ degrees, and the dislocation density has been $\approx 10^{-4}/\text{cm}^2$.

Vacuum chamber



The main descriptions of EPHCA program

The calculations have been made from the program packet of EPHCA [Bespalov V.I. Paket program EPHCA. Izv. Vuzov. Physika. Prilojenie 2000, №4. p. 159-165]. The program allows the modeling of trajectories of the following types of ionizing radiations of electrons, positrons, photons and protons to be performed:

The following types of particle interactions are taken into considerations:

elastic and ionizing collisions, Breamstrahlung radiation for electrons and positrons (annihilation effect for positrons);

Compton effect, photoeffect, electron-positron pair formation for photons. Photon trajectories are modeled in the individual collisions model. The trajectory formation of electrons, positrons and protons are performed in the model of low energy transmissions [Kolchuskin A.M., Uchaykin V.V. "Vvedenie v teoriyu proxojdeniya chastiz cherez veschestvo".-M.: Atomizdat, 1978], when the energy loss fluctuations in the far collisions and fluctuations as a result of multiple scattering are taken into considerations.

For the angle declination modeling of electrons and positrons in the end of the trajectory the three distributions are used:

Gowdsmith – Saunderson distribution in the energy range, less then 50 MeV;

Mollier distributions at the energy, less then 50 MeV;

'Keil'- distributions [Keil Von E., Zeitler, E. Zinn W.// Z. Naturforshung.– 1960, 15a,– p. 1031-1038] – for the way segments, for which the number of collisions, less then 20.

The modeling of energetic distribution of Bremstrahlung photon radiation and the calculation of energy loss for Breamstrahlung radiation is made according to the formulas Bethe – Gaitler []. In the energy range of 0,025 – 30 MeV these formulas are connected with more precise Pratt results according to the approximation expression from work [Koch H. W. and Motz J. W.// Rev. Mod. Phys.– 1959, V. 31, p. 920-955.]

The process of generation of the characteristic radiation is taken into account in the program for K and α atom shell as a result of photoabsorption and as a result of atom ionization by the charged particles.

Comparison of EPHCA and GEANT-4 calculations

The calculation results.

The calculations are given for the electron accelerator with the accelerating voltage of 1100 kV on the supposition that the accelerator generates disk monodirected monoenergetic electron beam with the energy of 1100 keV. The electron beam falls on the tungsten target.

In all calculations modeling 4 – 6 millions histories was performed.

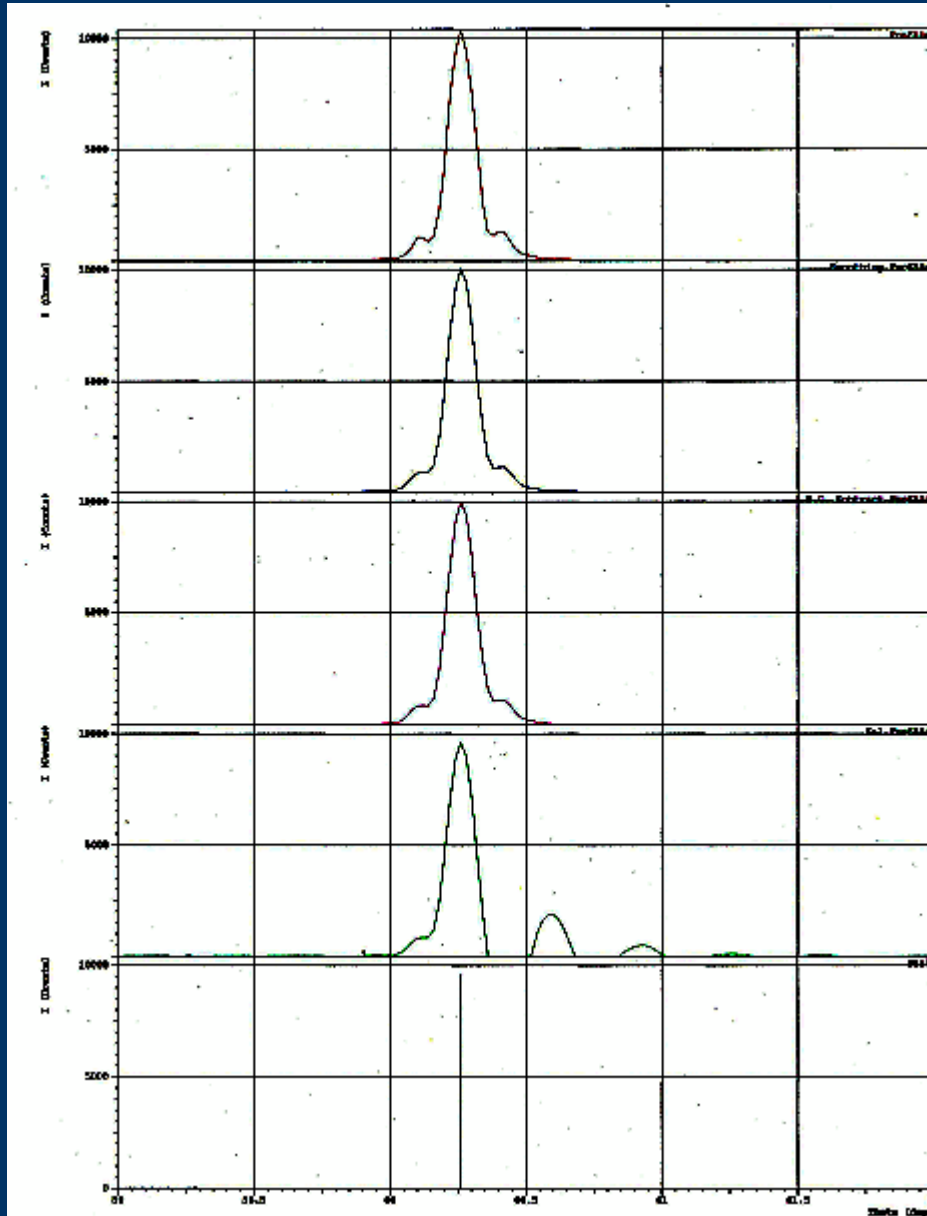
MONTE-CARLO:

Number of electrons per bunch-----	$7,8 \cdot 10^{13}$
Absorbed Electron Energy in Crystal -----	$0,687 \pm 0,003 \text{ MeV/e-}$
Reflected Electron Energy in Crystal -----	$0,411 \pm 0,003 \text{ MeV/e-}$
Passage Photon Energy throw Crystal -----	$0,01 \text{ MeV/e-}$
Reflected Photon Energy from Crystal -----	$0,014 \text{ MeV/e-}$

GEANT 4:

Number electrons per bunch-----	$6.23 \cdot 10^{13}$
Absorbed Electron Energy in Crystal-----	$0.65183 \pm 5 \cdot 10^{-5} \text{ MeV/e-}$

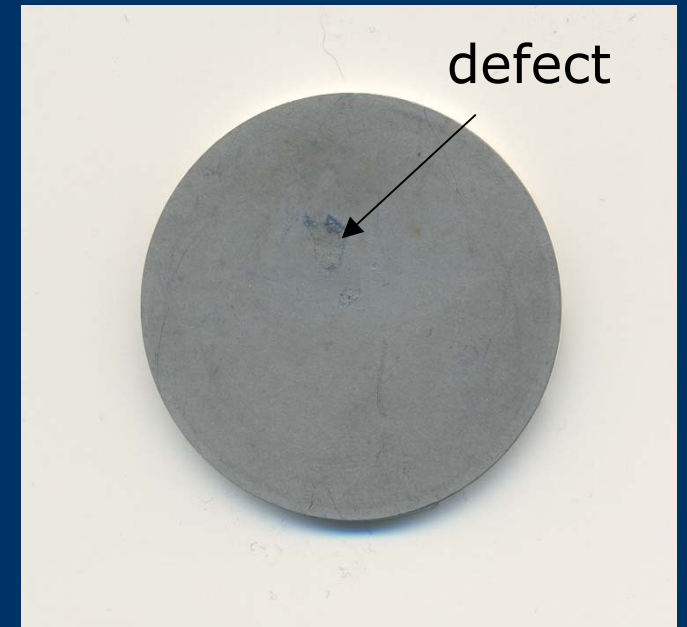
Rocking curve W



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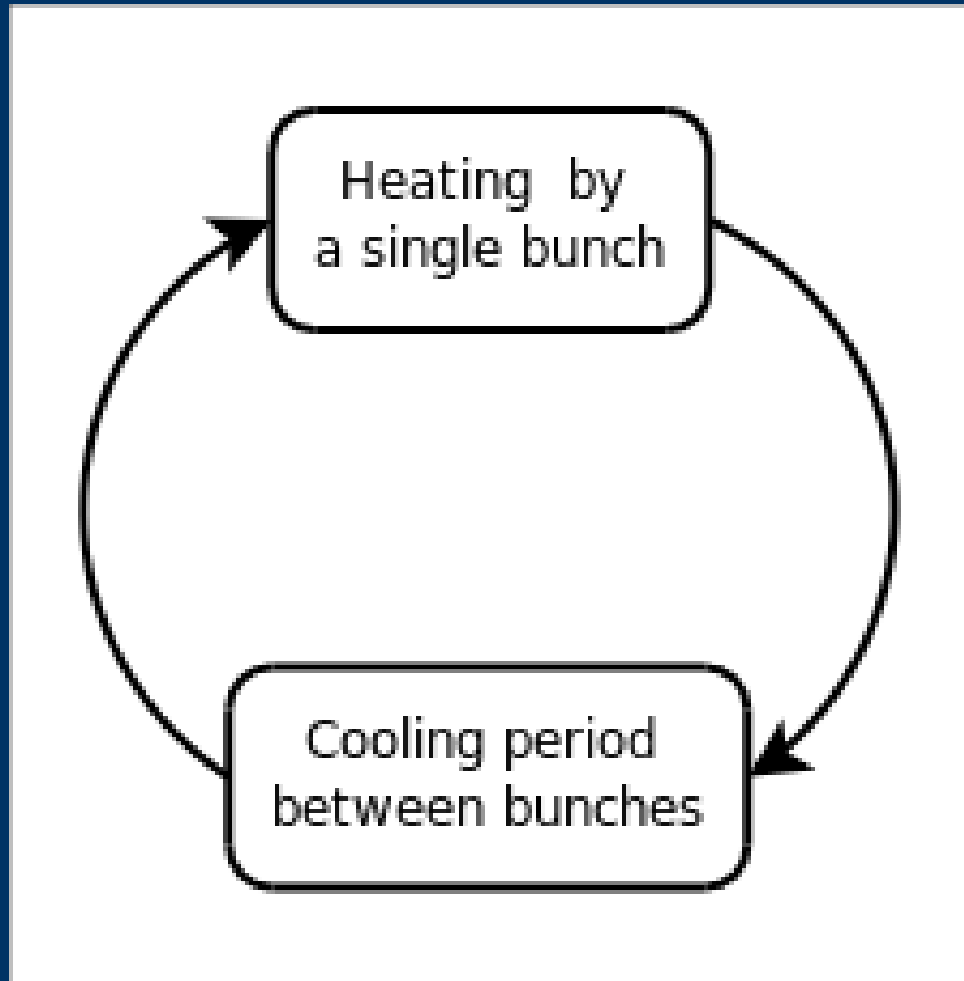
W - target

At the irradiation of the crystal the absorbed energy in the target material has been calculated by Monte-Carlo method [2] and has been 0.658 meV/electron. For the determination of the optimum conditions, at which the crystalline target structure is not broken after the powerful electron beam effect, the test experiment on the electron beam in the vacuum chamber of the accelerator “Sinus-7” have been made. After the irradiation with the exposure of 12 pulses the tungsten crystal has been deformed along the sphere surface with the radius of 86 cm.



**Photo W – target
after irradiation**

Life cycle of target:



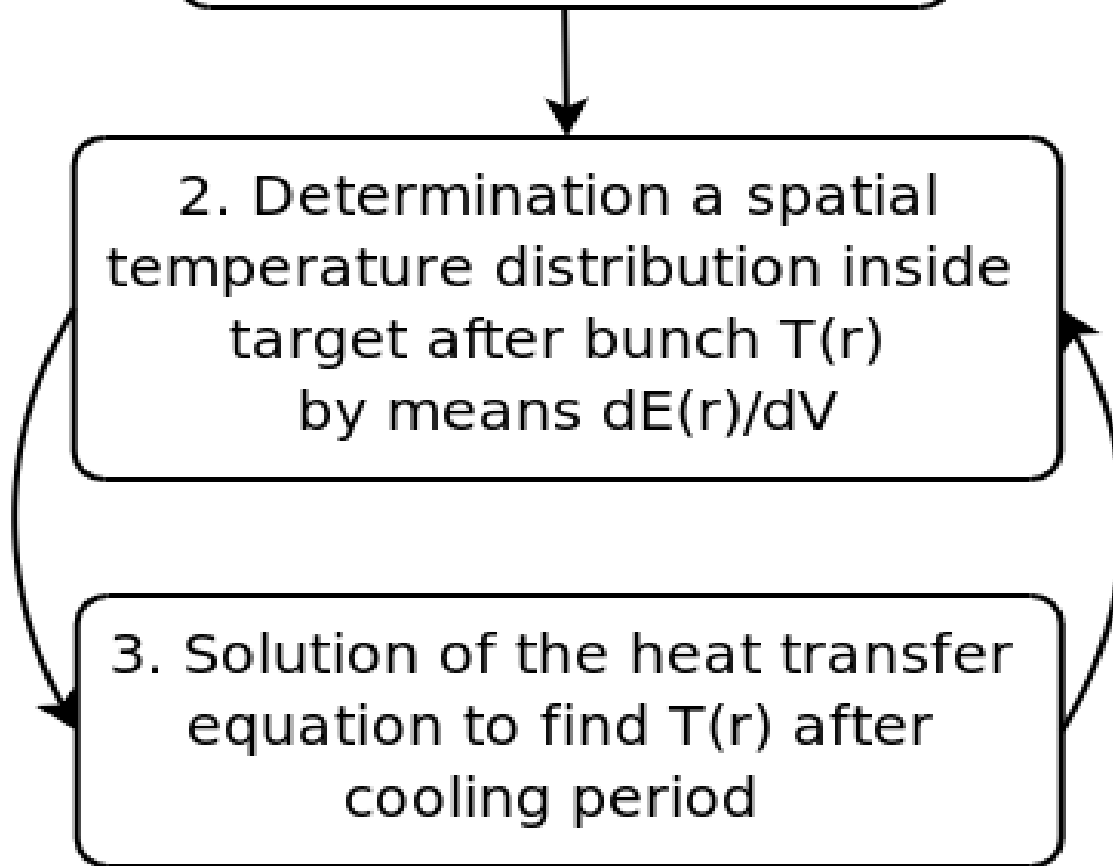
- In the model an energy deposition induced by single bunch considered as instant.
- Cooling period between bunches assumed to be $1/f$, where f – beam repetition rate.

Stages of simulation:

1. Calculation $dE(r)/dV$ - energy deposition induced by single bunch

2. Determination a spatial temperature distribution inside target after bunch $T(r)$ by means $dE(r)/dV$

3. Solution of the heat transfer equation to find $T(r)$ after cooling period



Calculation of energy deposition induced by beam bunch

- Math. model : Set of Boltzmann equations:

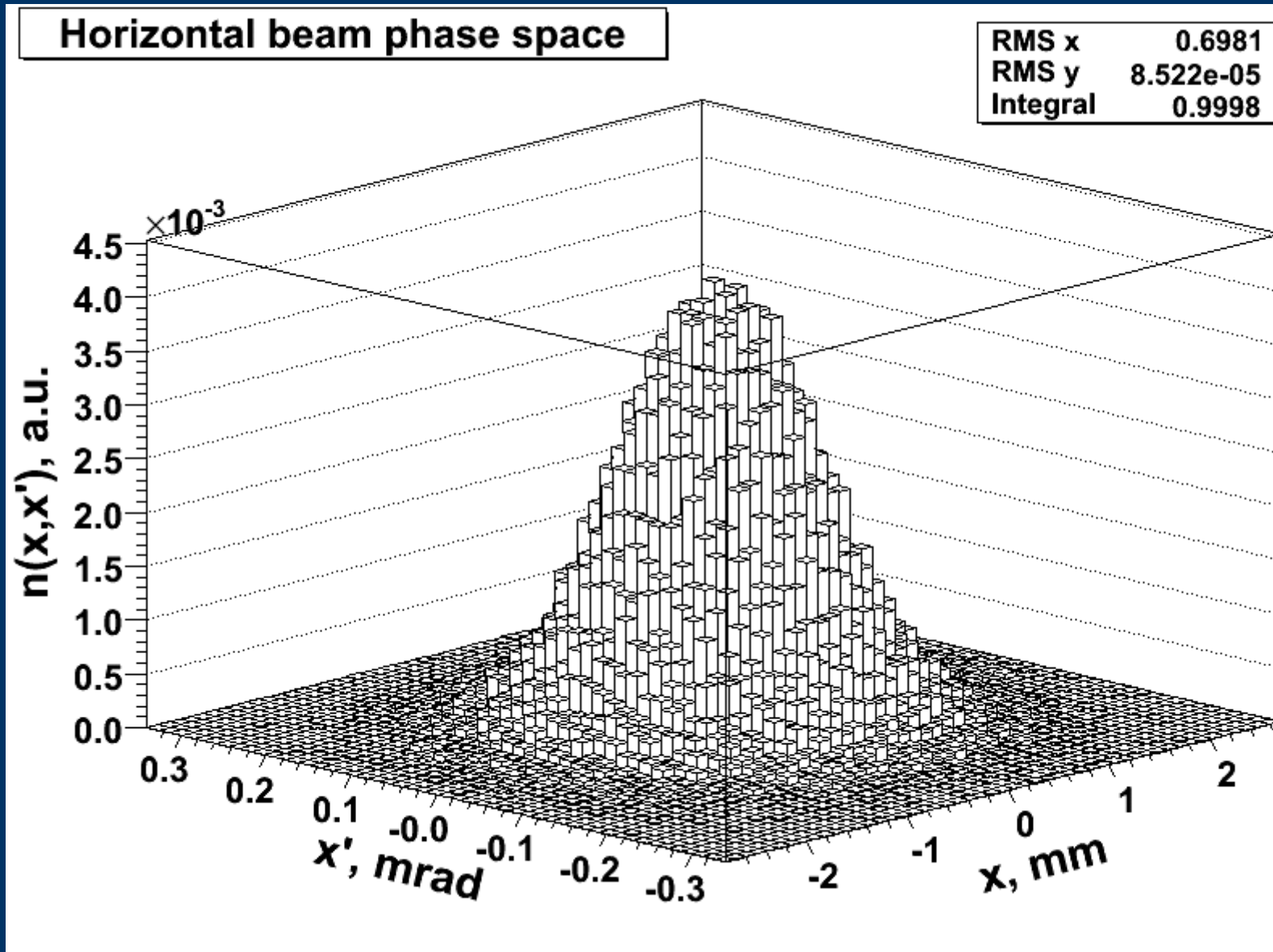
$$\vec{\Omega} \nabla \Phi_i(\vec{r}, \vec{\Omega}, E) + \Sigma_i(\vec{r}, E) \Phi_i(\vec{r}, \vec{\Omega}, E) + \sum_j \int d\Omega' \int dE' \Sigma_{j,i}(\vec{r}, \vec{\Omega}' \rightarrow \vec{\Omega}, E' \rightarrow E) \Phi_j(\vec{r}, \vec{\Omega}', E') = S(\vec{r}, \vec{\Omega}, E),$$
$$J = \int d\vec{r} \int dE \int d\vec{\Omega} \Phi(\vec{r}, \vec{\Omega}, E) D(\vec{r}, \vec{\Omega}, E)$$

- Particles in effect : photons (photo, Compton, pair production), electrons, positrons (bremsstrahlung, ionization)
 - Solution method: statistical testing – Monte Carlo
 - Tools : GEANT4, EPHCA
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Beam model parameters:

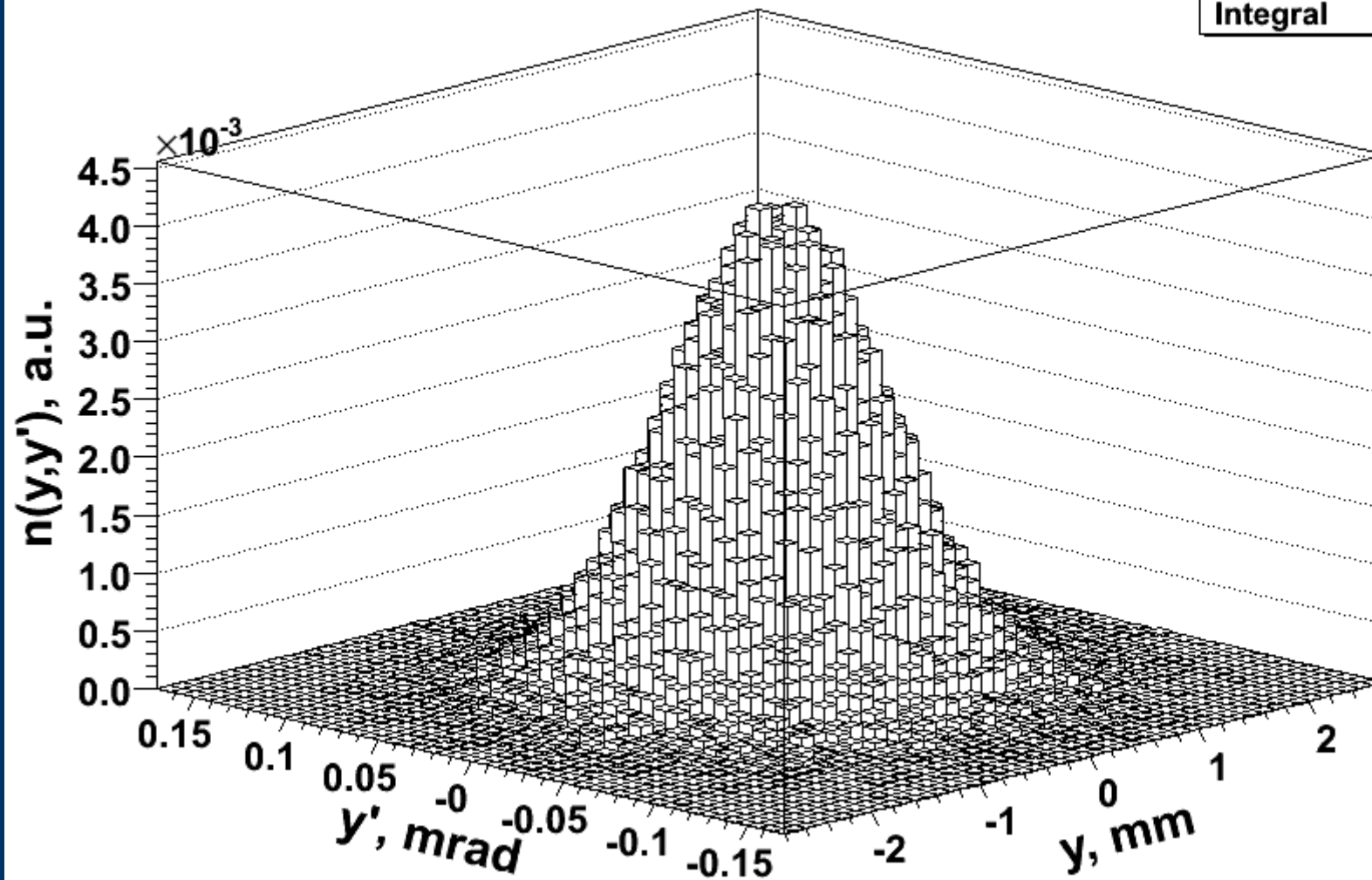
- Beam energy – 1,1 MeV .
- Bunch charge – $6.23 \times 10^{13} e^-$.
- Gaussian model is used for spatial – angular distribution of electrons .

Beam model:



Beam model:

Vertical beam phase space



RMS x	0.7007
RMS y	4.236e-05
Integral	0.9999

Determination a spatial temperature distribution after bunch:

- Math. Model:

$$\frac{d E(\vec{r})}{dV} = \rho \int_{T_0(\vec{r})}^{T(\vec{r})} du c(u)$$

where ρ - density, $c(u)$ - specific heat ,

$T_0(\vec{r}), T(\vec{r})$ - temperatures at \vec{r} before and after bunch, respectively.

- Method: Iterative procedure
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Heat transfer between bunches

- Math. model:
$$c(T) \rho \frac{\partial T}{\partial t} = \text{div}(k \text{grad} T)$$

- Boundary conditions : convective heat flux on upstream plane and side cylindrical surface of copper body:

$$k \frac{\partial T}{\partial n} + h(T - T_c) = 0, \quad T_c = 25^\circ \text{C}, \quad h = 0.93 \times 10^{-2} \text{ W/mm}^2 \text{ K}$$

- Initial condition: defined from solution of

$$\frac{dE(\vec{r})}{dV} = \rho \int_{T_0(\vec{r})}^{T(\vec{r})} du c(u)$$

with respect to the upper limit $T(\vec{r})$, $T_0(\vec{r}, t=0) = 25^\circ \text{C}$

- Solution method : Finite Volume Method (FVM)

Test example: Heat transfer in infinite tungsten cylinder.

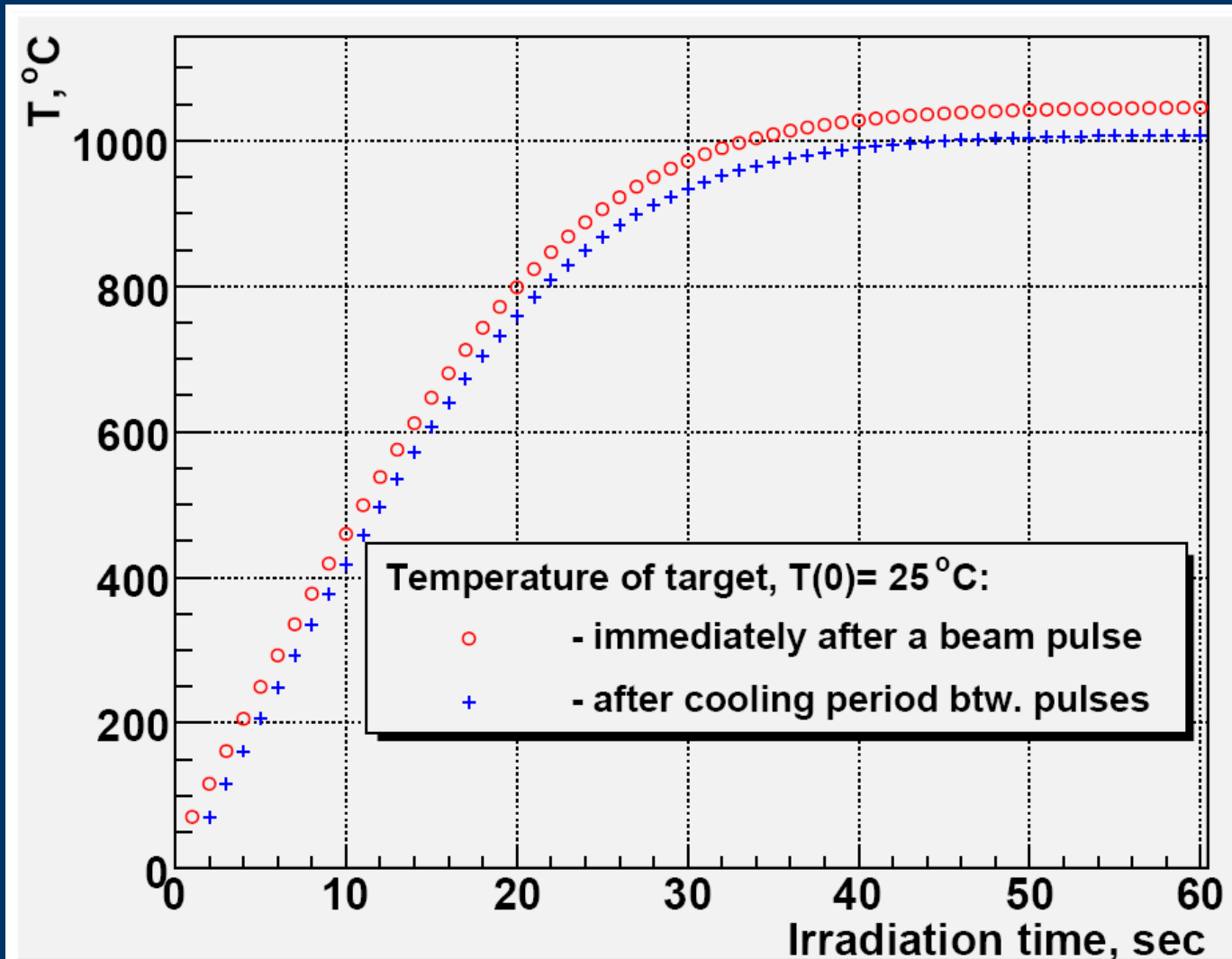
- Initial condition: $T(\rho, t=0) = 100 \exp\left(-\frac{\rho^2}{2\sigma^2}\right)$, $\sigma = 0.7 \text{ mm}$
- Boundary condition: convective flux,

$$T_c = 0^\circ \text{C}, \quad h = 0.015 \text{ W/mm}^2 \text{K}$$

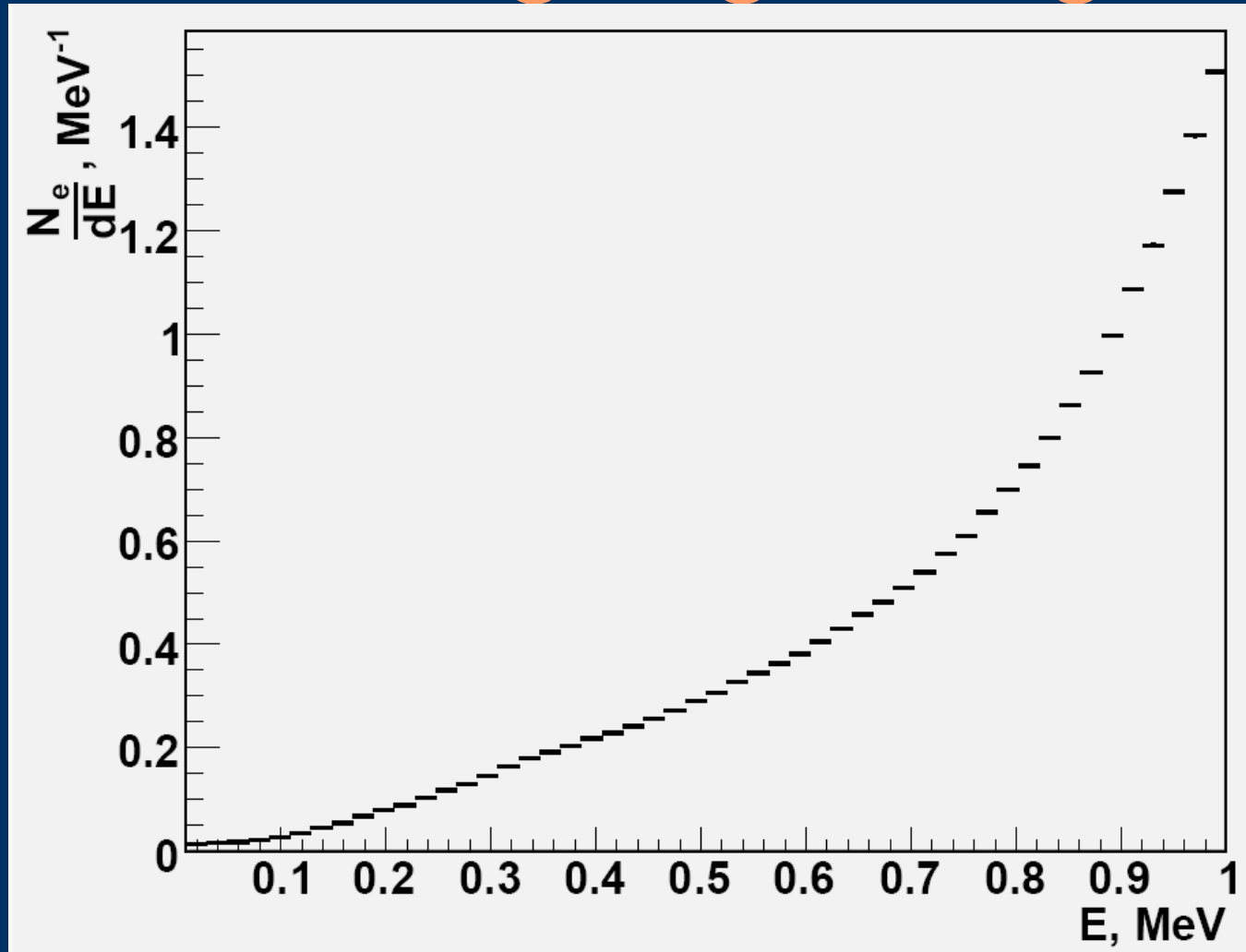
- Analytical solution:

$$T(\rho, t) = \frac{2}{\rho_0} \sum_{i=0}^{\infty} \exp(-\lambda_n^2 \alpha t) \frac{J_0(\lambda_n \rho)}{J_0^2(\lambda_n \rho_0) + J_1^2(\lambda_n \rho_0)}$$
$$\int_0^{\rho_0} \rho T(\rho, t=0) J_0(\lambda_n \rho) d\rho, \quad \lambda_n: \lambda \rho_0 \frac{J_1(\lambda \rho_0)}{J_0(\lambda \rho_0)} = \frac{h \rho_0}{k}$$

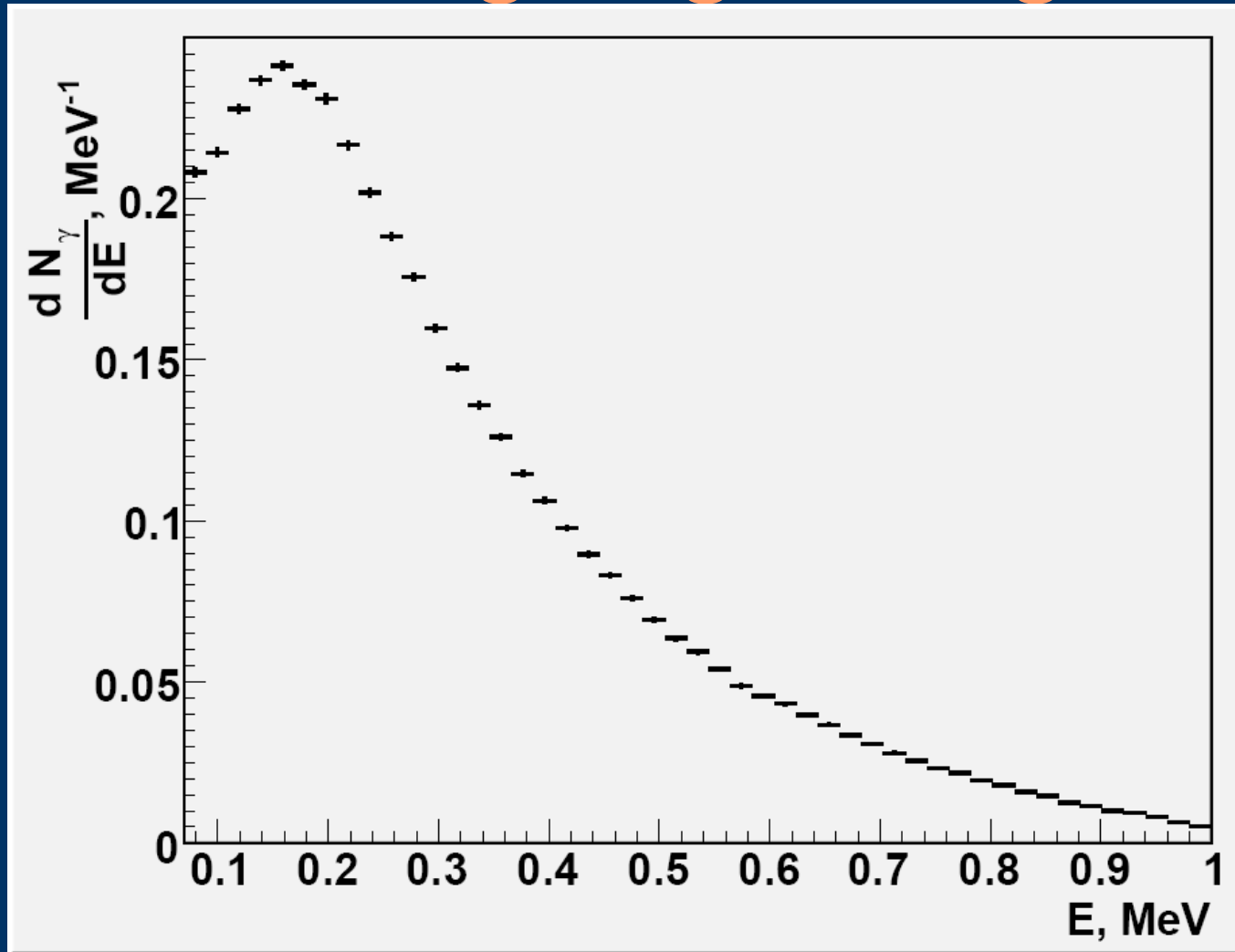
Max. temperatures before and after pulse as function of irradiation time for the 0.5mm Wa target



Spectrum of electrons outgoing of target



Spectrum of photons outgoing of target



Summary

- Simulations of temperature fields in W crystal under intense electron beam with nanosecond duration showed the temperature rise $\sim \Delta t = 100^\circ\text{C}$ after first pulse.
- For our conditions ($\tau = 12$ sec, $N_e = 7.8 \cdot 10^{13}$ per pulse) saturation temperature $t = 1200^\circ\text{C}$ is achieved after 12 pulses.
- After 12 pulses ($N_e = 12 \cdot 7.8 \cdot 10^{13}$) flat W target becomes as spherical one with radius 86 μm .
- Comparison of rocking curves for flat and deformed crystal targets showed there are no difference.

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