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THE HIGH-CURRENT DEUTERON ACCELERATOR FOR THE NEUTRON THERAPY

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THE PROJECT OF NEUTRON SOURCES FOR THE NEUTRON THERAPY AND NEUTRON ACTIVATION ANALYSIS

- **The high-current accelerator of deuterium ions (HCADI)**
Energy of deuterium ions - **430 keV**
Average current - **20 mA**.
- **T(d,n)⁴He** reaction
Fast neutrons (**~14 MeV**) - intensity up to **5·10¹² n/s**
- **D(d,n)³He** reaction
Fast neutrons (**~ 3 MeV**) - intensity up to **5·10¹⁰ n/s**
- ***Neutron source for the fast neutron therapy
neutron capture***

therapy

Behaviours of neutron irradiation

- Neutron is electrically neutral; it easily penetrates into atomic nucleus and initiates different nuclear reactions.
- Probability of reaction strongly depends on neutron energy and features of nucleus which neutron is contacting with.
- Neutron colliding nucleus may scatter and moderate transferring its energy to a matter.
- Neutrons with energy equal to thermal energy of atoms are called thermal ones (average energy = 0.0253 eV)
- Neutrons with energy above 100 keV are called fast ones.

Penetration of the neutron radiation

Number of neutrons N which did not endure any collisions with nuclei

$$N(x) = N_0 \exp(-n_0 \sigma_t x)$$

N_0 – number of neutrons in the beam;

n_0 – number of nuclei in a unit of volume;

σ_t – total effective cross-section;

x – thickness of a matter layer.

Fast neutron therapy (FNT)

- Fast neutrons penetrate into matter and moderate.
- Energy transferred to matter by a fast neutron leads to ionization and excitation of atoms and molecules, dissociation and generation of free radicals, initiates different chemical reactions.
- This is creating absorbed dose and kill- effect in cancer cells of malignant neoplasm .

Exponential reduction of the absorbed dose relating to penetration depth.

Neutron capture therapy (NCT)

- During thermal neutron irradiation, secondary radiation (alpha, γ - ray, electron, X-ray) are produced by nuclear reactions (thermal neutron capture) in the material.
- Secondary particles traversing the cell nucleus suffice to lead to ionogenic death.

This is creating absorbed dose and kill- effect in cancer cells.

- High therapeutic effect NCT– ratio of dose in a tumor to maximal dose in healthy tissue.
Relative biologic effectiveness (RBE) secondary radiation varies from 2-3 to 10.

NCT is used for medical treatment of complicate malignant neoplasm as multiform glioblastoma of brain, anaplastic astrocytoma, melanoma and its metastases.

^{10}B neutron capture reactions (BNCT)



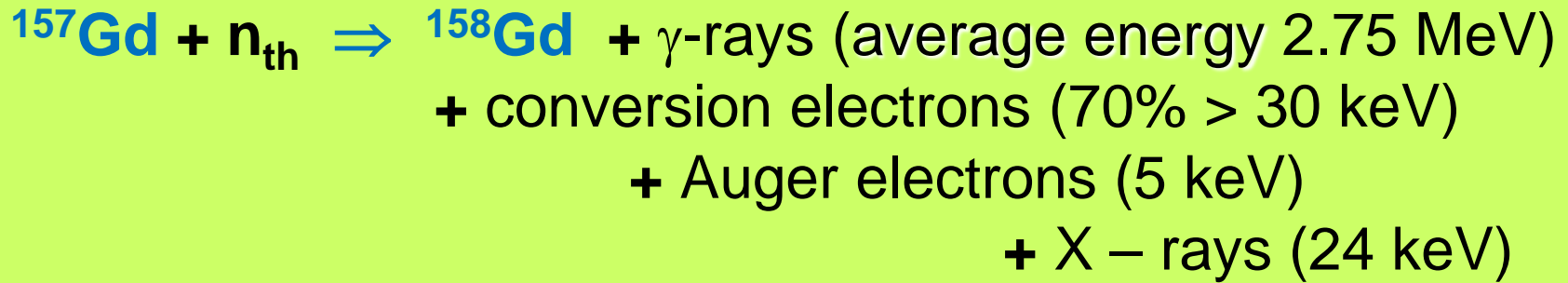
$\sigma_t = 3,800$ barns,

the α -range is of $\sim 10 \mu\text{m} <$ cell dimensions

Concentration of ^{10}B into the tumor cell should be of $\sim 10^9$ atoms
with **ratio** of boron concentration **tumor/normal tissue** > 3

Sodium mercaptododecaborat $\text{C}_2\text{B}_{12}\text{H}_{11}\text{SH}$ (**BSH**) is used as
boron carrier for transferring ones to the tumor.

Gd neutron capture reactions



$\sigma_t = 242,000$ barns,

The conversion electron range is of 20-100 μm ~ cell dimensions

Concentration of ^{157}Gd outside **concer** cell can be of $\sim 10^{10}$ atoms

The microparticles of the liquid-crystalline dispersion of the (DNA-Gd) complex is used as ^{157}Gd carrier.

The nanoparticle of the (DNA- Gd) contains 10^7 atoms ^{157}Gd .

THE POWERFUL NEUTRON GENERATORS (NG)

- In Russia powerful neutron generators (**NG**) produces **NIIEFA**, **NG-12-2I**, provides a flow of DT neutrons of $\sim 2 \cdot 10^{12} \text{ n} \cdot \text{s}^{-1}$ at an accelerating voltage of **250 kV** and a current of **10 mA**.
- The foreign producers of NG - the firm "**IRELEC**" (France), **HCADI** - at voltage of **430 kV** and a current of **20 mA**.

The **DT** neutron flux (**14 MeV**) on target is of $5 \cdot 10^{11} \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$

The **DD** neutron flux (**3 MeV**) on target is of $5 \cdot 10^9 \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$

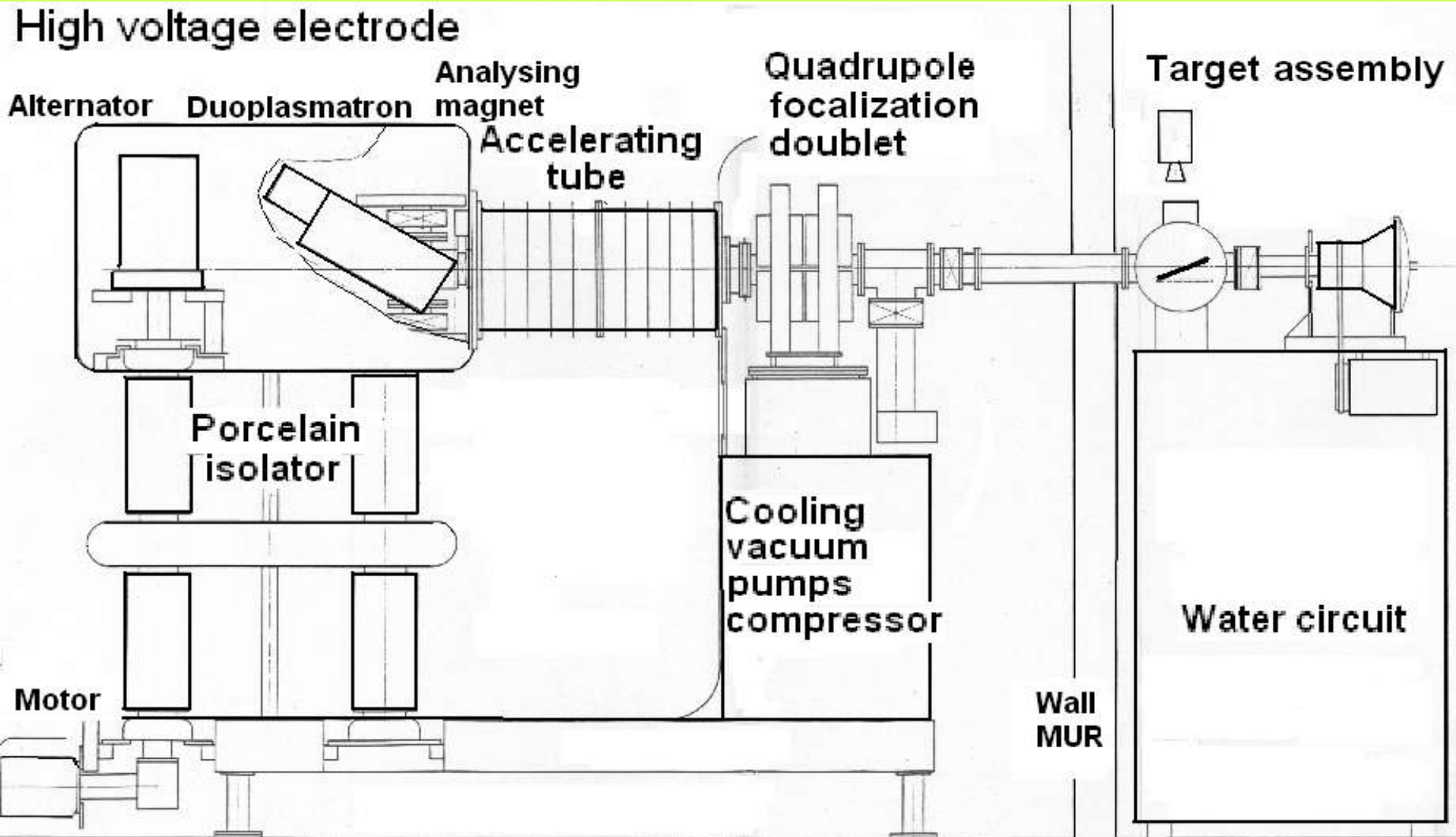
DEUTERON ACCELERATOR

- **An electrostatic particle accelerator**, supplying a 20 mA / 430 kV beam of monoatomic deuterium ions (D^+).
- **A target assembly**, the retractable target designed for beam adjustment, the rotating target containing the tritiated layer, cryopump, the target water cooling system
- **An high voltage DC power supply** (an ISU type), providing the acceleration voltage (400 kV – 30 mA) consists of a transformer set.
- **A control and monitoring system**, includes the Control Bay, centralizing the controls, adjustments for the various beam parameters, operating modes, fault indications and safety.

THE ELECTROSTATIC PARTICLE ACCELERATOR

- The HV electrode (400 kV) including the vacuum chamber of the injector, deflecting magnet, the ion source equipment, the alternator supplying power to the HV electrode .
- The accelerating tube (a rated voltage of 400 kV)
- The quadrupole focalization double (a throat diameter is of 102 mm, a nominal gradient is of 1.9 T/m)
- The extension tube, leading to the targets assembly (a distance of 3.3 m).

THE HIGH-CURRENT DEUTERON ACCELERATOR



THE INJECTOR

- The ion source (the duoplasmatron type). Oven-heated oxide cathode has lifetime > 300 h for discharge current and voltage of $15 \text{ A} \times 150 \text{ V}$.
- The beam (50% D^+ , 50% D^+_2) extraction optics (the pierce type) has current of 55 mA.
- The atomic ion analysing magnet (0.4 T).

The plasma expands through the anode into a expansion cup.

ACCELERATING TUBE AND QUADRUPOLE DOUBLE

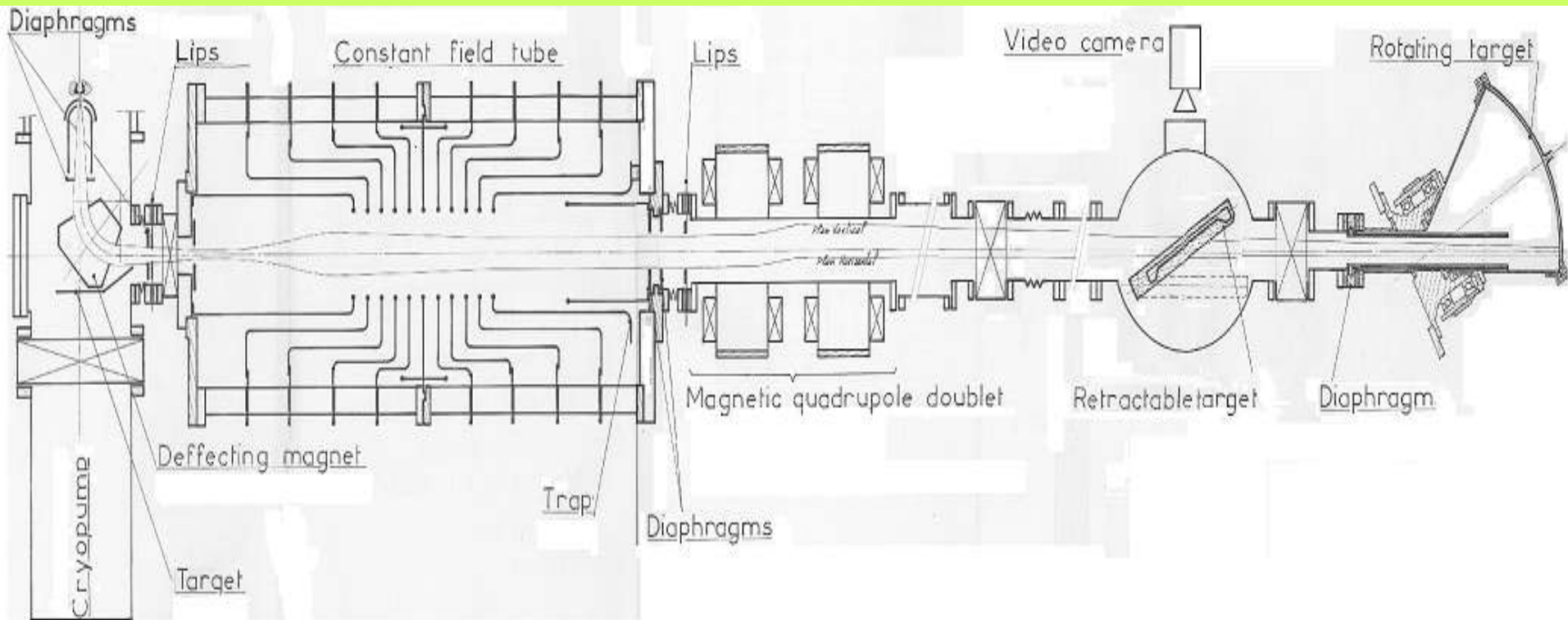
- Accelerating tube consists of two half-length tubes, each made up of 5 porcelain rings and electrodes, providing a 12.5 kV/cm outside the accelerating space.

A rated voltage, diameter and length of the tube are 400 kV, 0.5 m and 1.03 m respectively.

- To compensate for divergence and to adjust the impact dimension, a quadrupole doublet is located.

A throat diameter and a nominal gradient of the doublet are 102 mm and 1.9 T/m respectively.

BEAM LINE



THE TARGET ASSEMBLY

The retractable target used to focus the beam by examining the impact dimension (a 20 -80 mm beam diameter) on a tantalum network through a window using a video camera .

The power of the beam (8.6 kW) is determined by a calorimetric measurement of the cooling water.

The rotating target (1500 rpm) consists of a 345 mm diameter spherical double seal to ensure an air-tight vacuum.

The axis of rotation is shifted by 30° with respect to the beam.

The target are water cooled and has lifetime ~ 150 h.

ACCELERATOR PARAMETERS

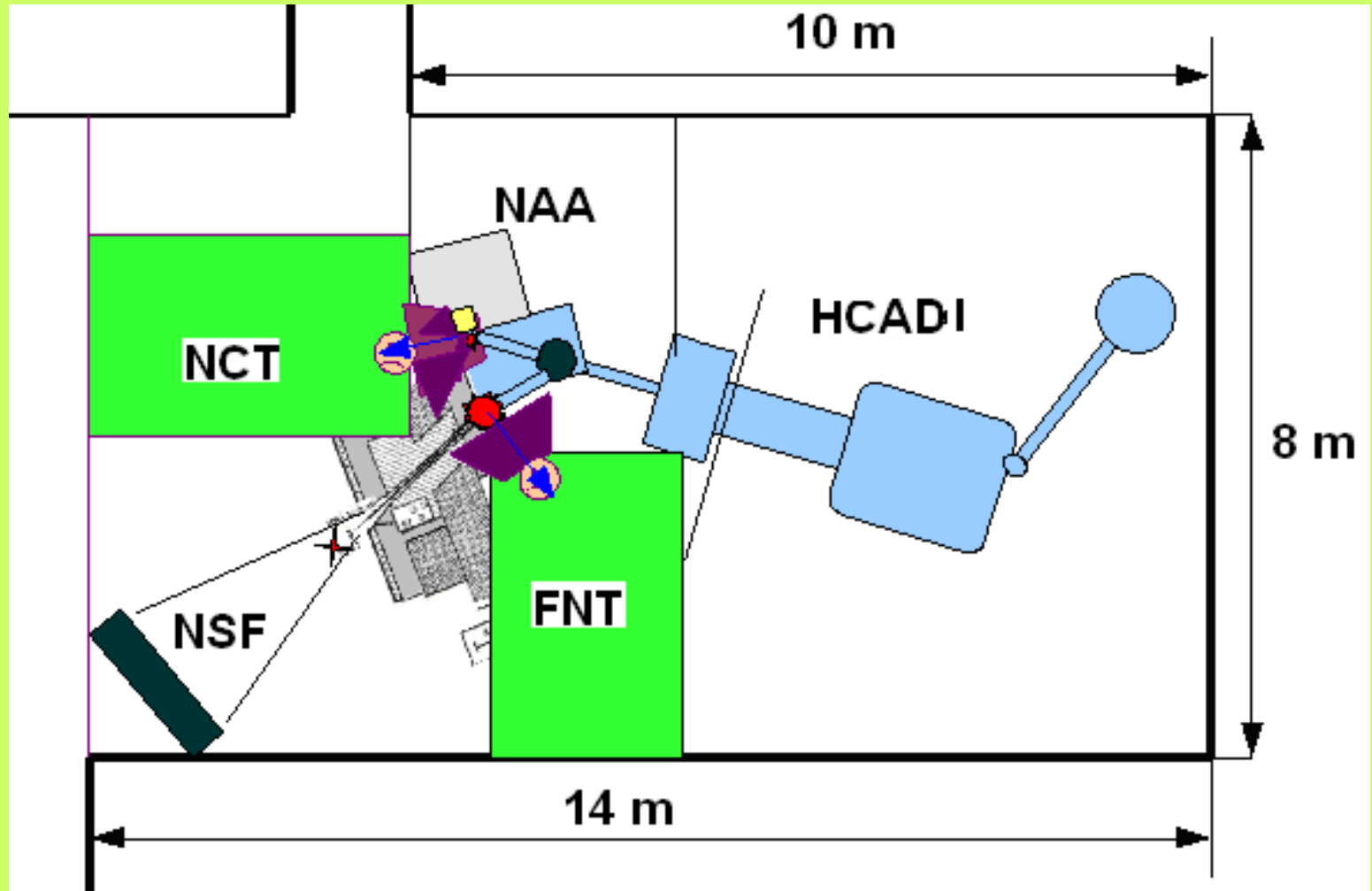
- Overall dimensions of the deuteron accelerator are **10×1.7×3 m**.
- A power consumption is about **60 kW**.
- Dangers related to the use of the accelerator is
 - 400 kV high voltage of the HV electrode,
 - X-rays of secondary electrons at the entrance to the accelerating tube,
 - neutron radiation,
 - radiation from neutron activation,
 - high radioactivity of the target (1000 curies).

NEUTRON FACILITY

The compact neutron sources based on **HCADI** for

- the fast neutron therapy (FNT),
- the neutron capture therapy (NCT),
- the neutron activation analysis (NAA),
- the neutron scattering facility (NSF).

The layout compact neutron sources and facilities



Neutron flux in facilities

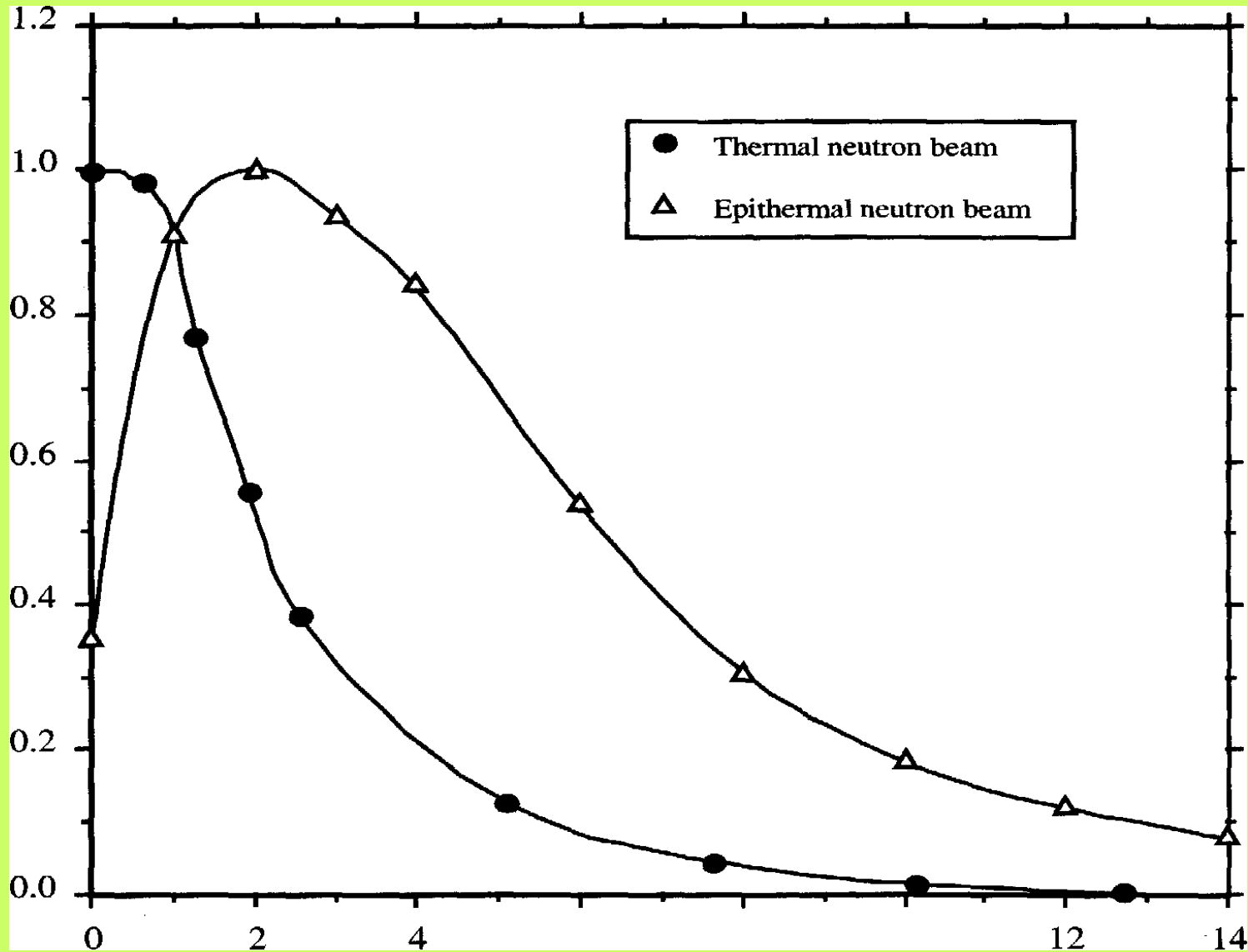
- Thermal neutron flux at moderation DT neutrons in **NAA facility** is of $1 \cdot 10^{10} \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$.
This can be used for the element quantitative Determination (the sensitivity is of 1 ng).
- Fast neutron flux in **NSF facility** - $1 \cdot 10^7 \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$.
nd – scattering, nn – interection

NEUTRON THERAPY FACILITY

- The fast neutron flux in FNT facility is of $1 \cdot 10^8 \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$
This is creating absorbed dose of $\sim 10 \text{ Gy}$ and kill- effect in cancer cells.
- **The neutron beam in NCT facility contains thermal and epithermal neutrons (0.5 eV – 10 keV).**

The neutron beam intensity would be above $5 \cdot 10^8 \text{ n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ in order to provide above 10 Gy in a tumor within an hour.

The neutron creating absorbed dose into matter



Monte-Carlo calculations and neutron activation measurements were made for evaluating of neutron specter from the moderater

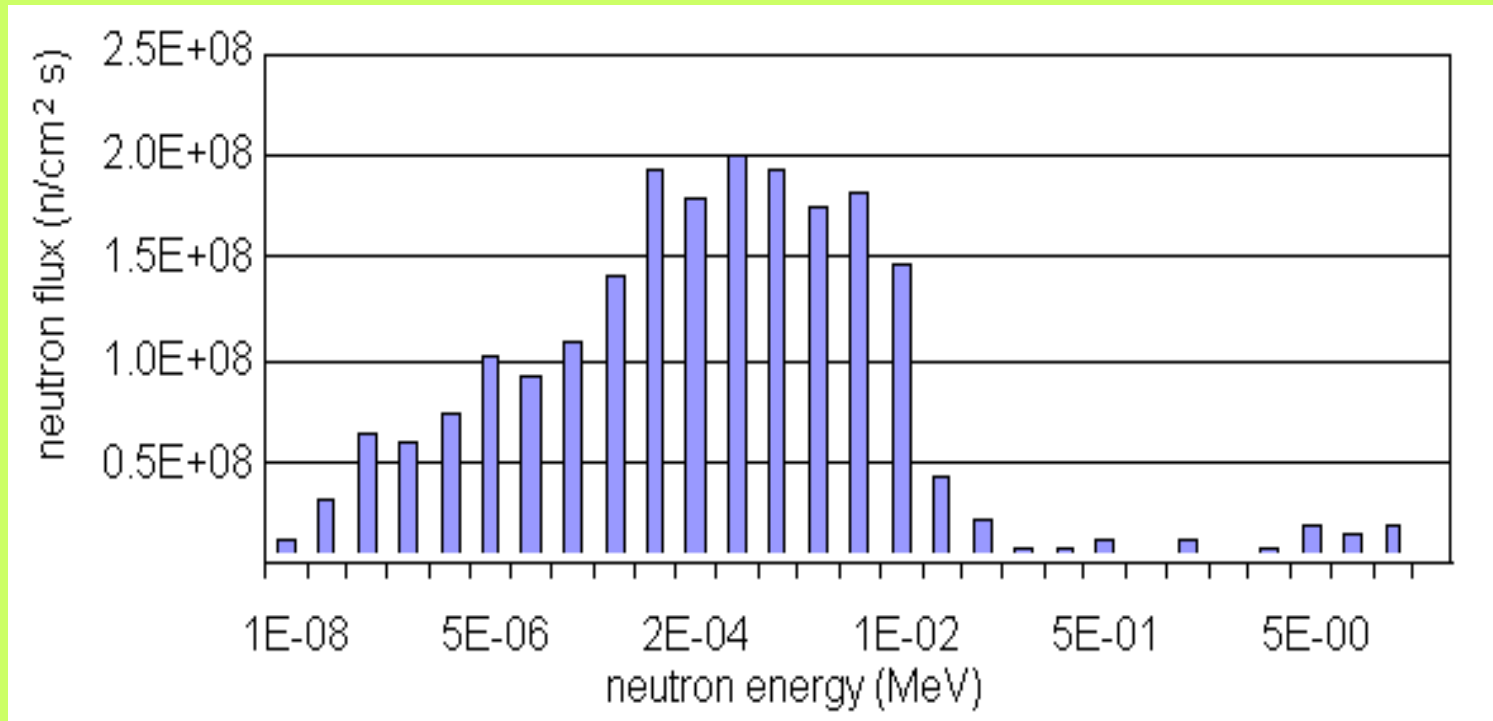
Converter + Moderater	<i>The epithermal neutron flux</i>	<i>The thermal neutron flux</i>	<i>The fast neutron flux</i>
UO₂ + H₂O	2·10⁷ cm⁻²s⁻¹		
BeO + H₂O	2·10⁷ cm⁻²s⁻¹		
W + H₂O	2·10⁷ cm⁻²s⁻¹		
W + D₂O	1·10⁹ cm⁻²s⁻¹		
Pb + H₂O	3·10⁷ cm⁻²s⁻¹		
W + graphite	1·10⁹ cm⁻²s⁻¹		

Thickness of converter - 15cm; Thickness of moderater 25cm

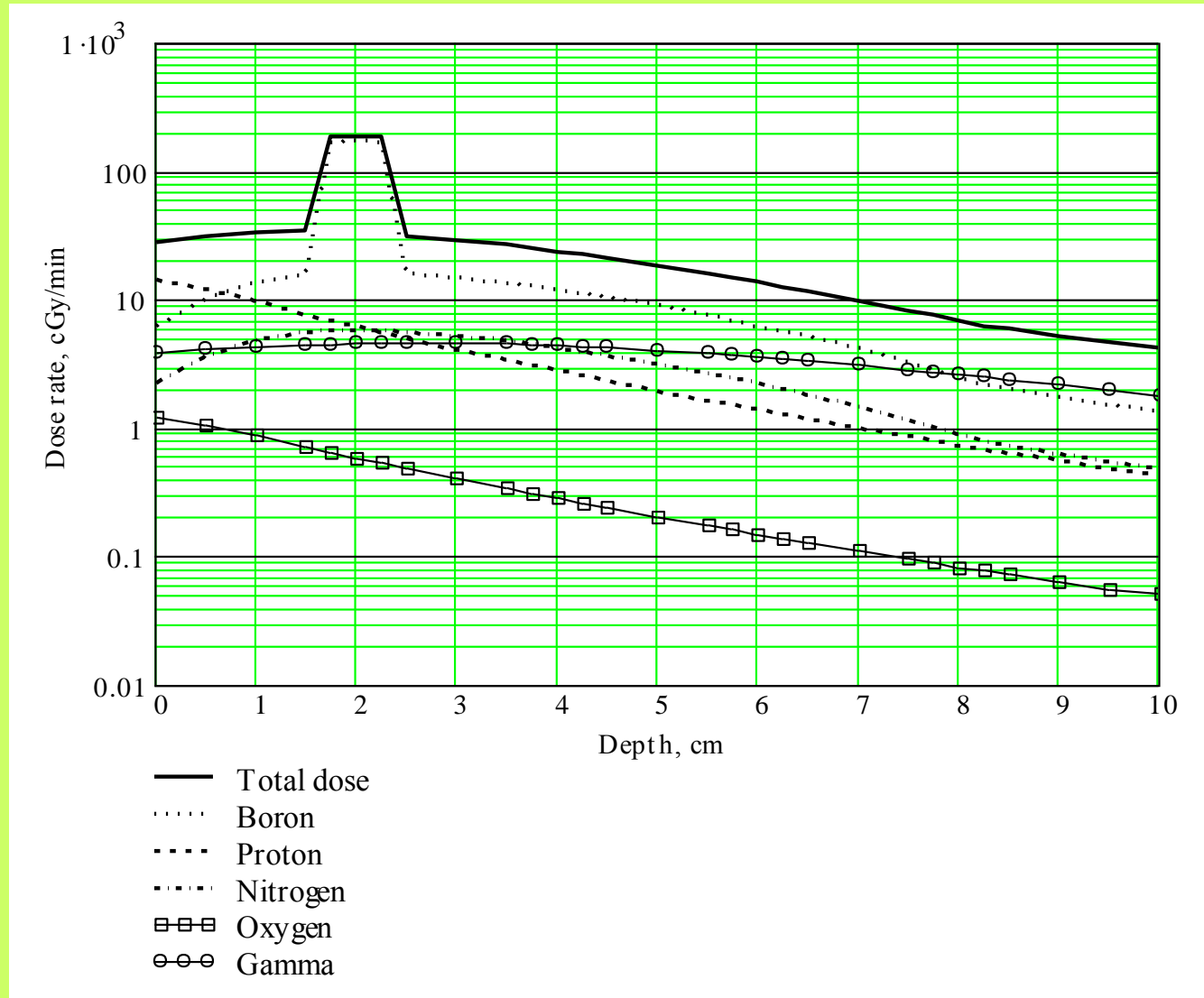
2·10⁸ cm⁻²s⁻¹

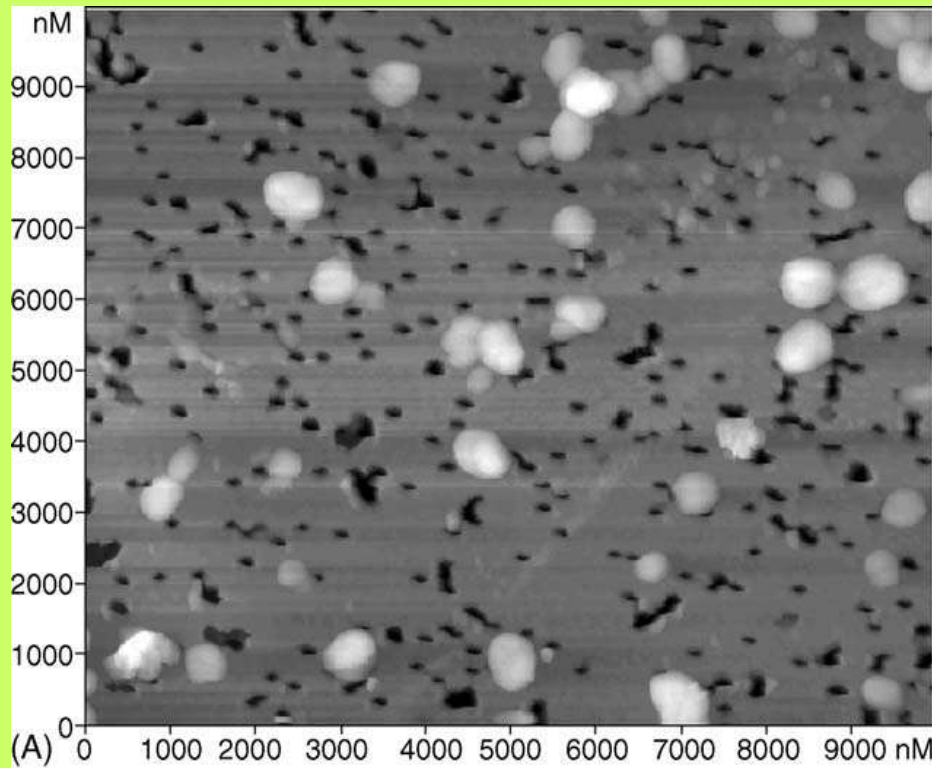
1·10⁷ cm⁻²s⁻¹

The spectrum of neutrons out the channel

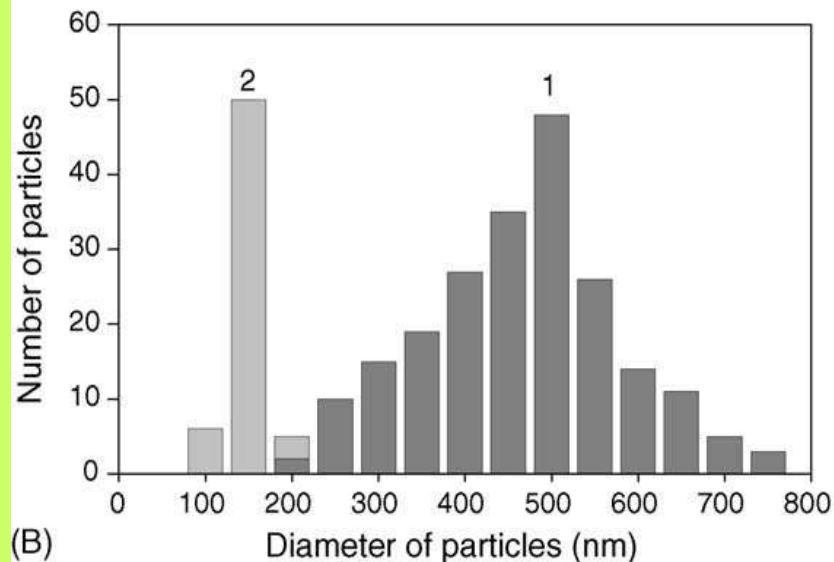


The neutron creating absorbed dose into matter from $^{10}\text{B}(n,\alpha)$ reaction

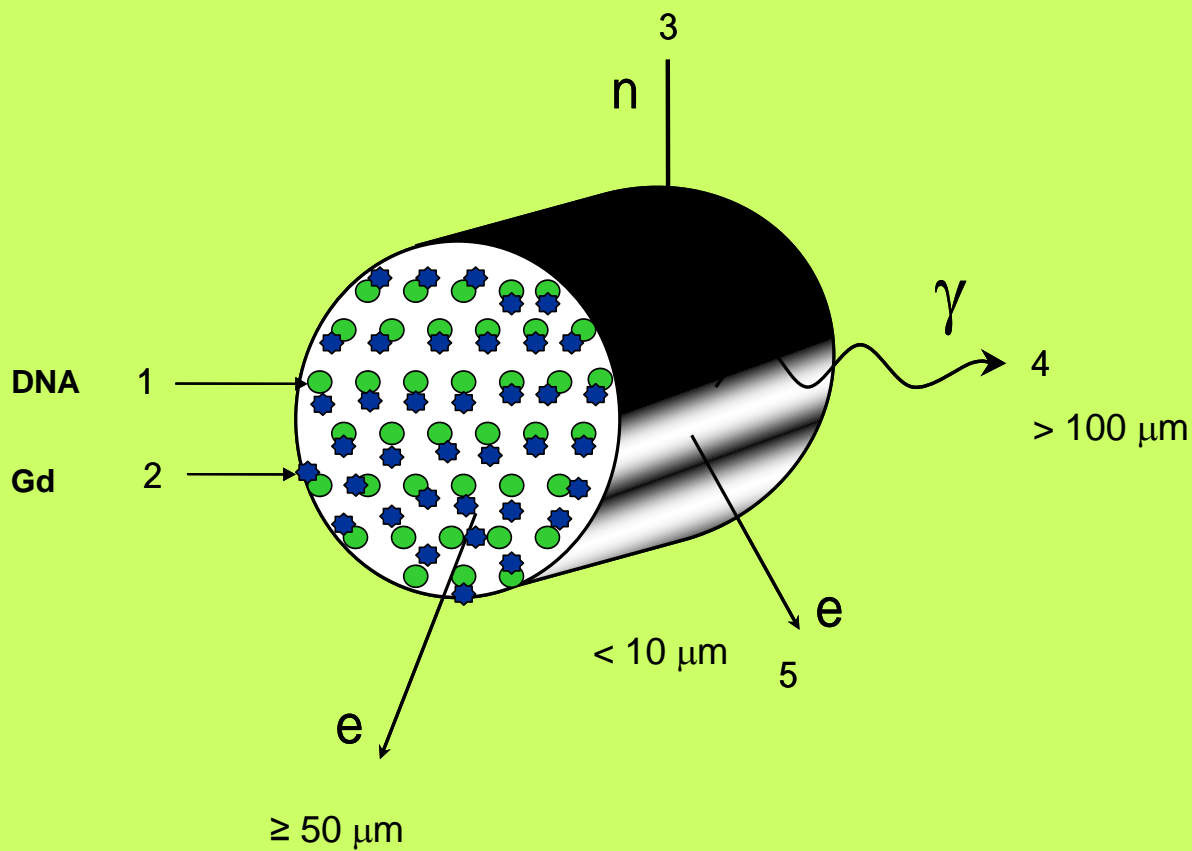




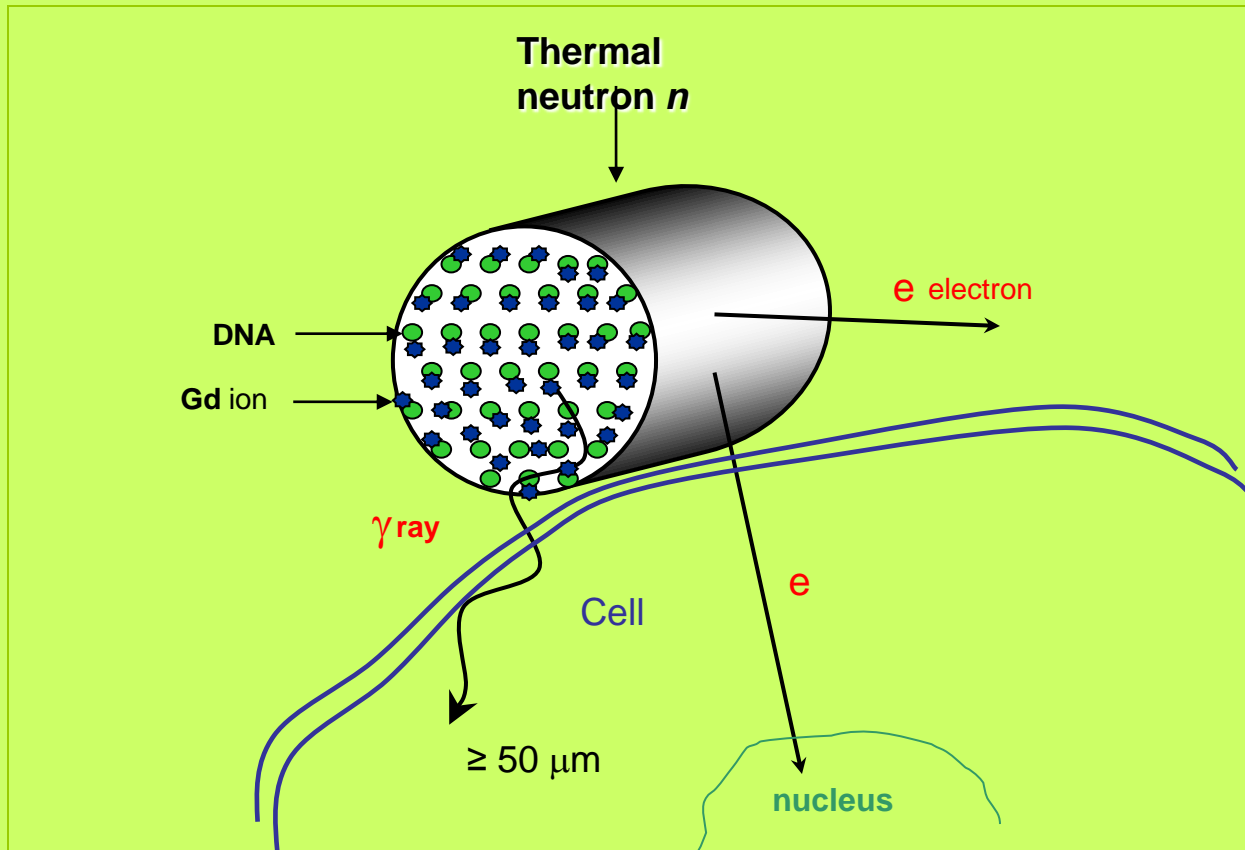
The image of the liquid-crystalline DNA-Gd microparticles immobilized onto the surface of the nuclear membrane filter



The neutron capture reactions in the (DNA-Gd) microparticle



The kill neighbor tumor cell by neutron capture reactions in the (DNA-Gd) microparticle



THE DNA-GD RBE RESEARCH

The biological samples containing cell suspension and DNA-Gd particles has been irradiated into the polyethylene Phantom (the size 20×20×20 cm) by fast DT neutrons from generator NG-400 (the intensity is of $2 \cdot 10^{11}$ n/s.).

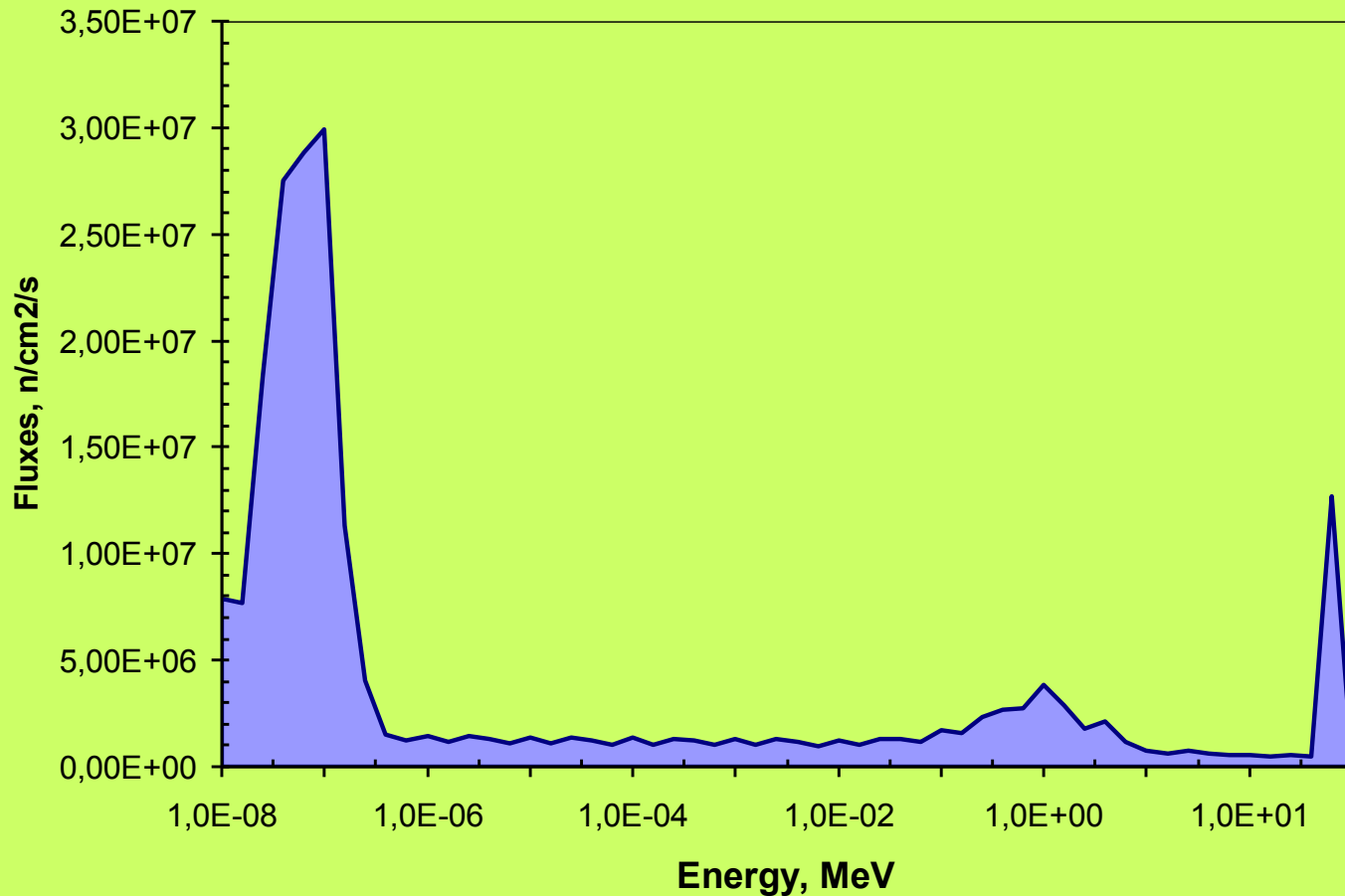
The thermal and fast neutron fluxes for each biological sample were measured by means of the NAA.

The killing of a major part of tumor cells in biological samples with nanoparticles was produced the thermal neutron fluence about $5 \cdot 10^{11}$ cm⁻² for a particle density of of 10^3 particles per cell.

We have identically irradiated two sets of samples: one is the cell culture added with the DNA-Gd particles, and another one is the cell culture without these particles.

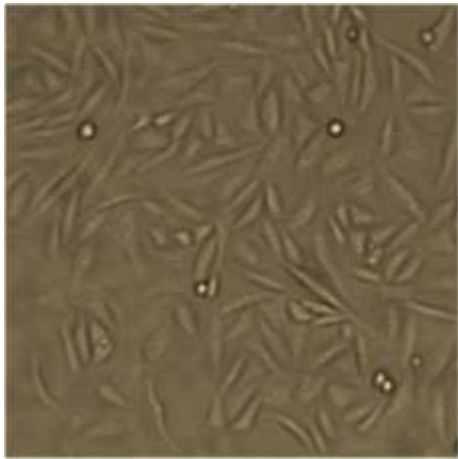
Spectrum of the neutrons from moderator system of the neutron sources NG-400 for the RBE research

Neutron fluxes

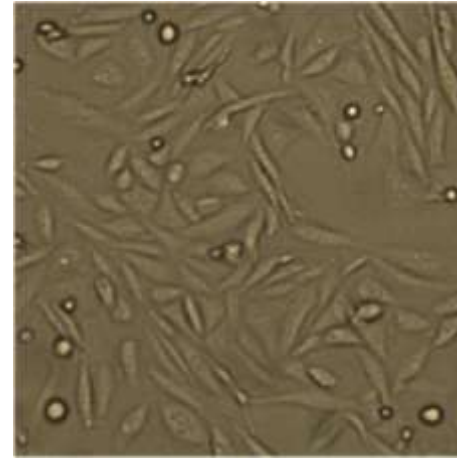


Neutron-capture therapy

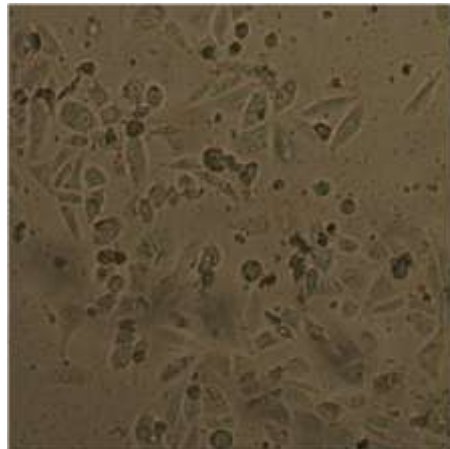
DESTRUCTION OF CELLS AS A RESULT OF ACTION OF SECONDARY IRRADIATION



Initial cells



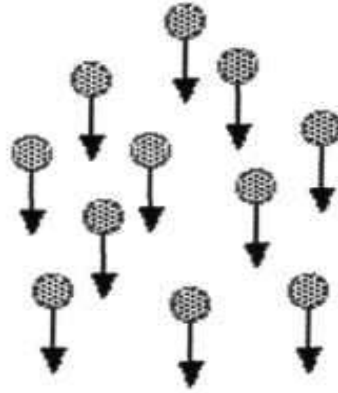
Initial cell + 30 min.
irradiation with
thermal neutrons



Initial cells + LC carrier of Gd
+ 30 min. irradiation with
thermal neutrons

The cells have been destroyed !

Epithermal neutrons



NCT in the tumor

Thermal neutrons

