Using even low-power sources of millimeter waves, the local increase in temperature of the sample can be several degrees. At the same time, the results indicate the absence of non-thermal effect of millimeter waves on the water.

The application of non-contact temperature sensing based on the temperature sensitivity of florescent dyes is a simple and novel method to detect temperature change in biological objects irradiated by millimeter waves.

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Submitted on 06.10.14

Бабіч Д., студ., Кузькова Н., асп., Попенко О., студ., Якунов А., канд. фіз.-мат. наук,
кафедра оптики, фізичний факультет
Київський національний університет імені Тараса Шевченка

ВИМІРЮВАННЯ ТЕМПЕРАТУРИ В СИТЕМІ ОПРОМІНЮВАНІЙ ЕЛЕКТРОМАГНІТНИМИ ХВИЛЯМИ МІЛІМЕТРОВОГО ДІАПАЗОНУ З ВИКОРИСТАННЯМ ТЕМПЕРАТУРОЗАЛЕЖНИХ ФЛУОРЕСЦЕНТНИХ ОРГАНІЧНИХ БАРВНИКІВ

Температурну чутливість флуоресценції розчинів органічних барвників використано для безконтактного вимірювання поглинання електромагнітних хвиль міліметрового діапазону у воді. За допомогою двох барвників з протилежними температурними ефектами визначено локальне підвищення температури в капілярі, розміщеному в середині прямокутного хвилеводу.

Застосування безконтактного температурного датчика є новим, простим методом визначення зміни температури малих біологічних об'єктів.

***Ключові слова:** міліметрові хвилі, безконтактне вимірювання температури, флуоресценція, органічні барвники, вода, біомедичне застосування.*

Бабич Д., студ., Кузькова Н., асп., Попенко А., студ., Якунов А., канд. физ.-мат. наук,
кафедра оптики, физический факультет
Киевский национальный университет имени Тараса Шевченко

ИЗМЕРЕНИЯ ТЕМПЕРАТУРЫ В СИСТЕМЕ ОБЛУЧАЕМОЙ ЭЛЕКТРОМАГНИТНЫМИ ВОЛНАМИ МИЛЛИМЕТРОВОГО ДИАПАЗОНА С ИСПОЛЬЗОВАНИЕМ ТЕМПЕРАТУРОЗАВИСИМЫХ ФЛУОРЕСЦЕНТНЫХ ОРГАНИЧЕСКИХ КРАСИТЕЛЕЙ

Температурная чувствительность флуоресценции растворов органических красителей использована для бесконтактного измерения поглощения электромагнитных волн миллиметрового диапазона в воде. С помощью двух красителей с противоположными температурными эффектами определено локальное повышение температуры в капилляре, размещенном внутри прямоугольного волновода.

Применение бесконтактного температурного датчика является новым, простым методом определения изменения температуры малых биологических объектов.

***Ключевые слова:** миллиметровые волны, бесконтактное измерение температуры, флуоресценция, органические красители, вода, биомедицинское применение*

UDC 539.1.03; 621.039.76

B. Bondar, Engineer-physicist, Clinical Hospital "Feofaniya",
Nuclear physics department, Taras Shevchenko National university of Kyiv
I. Mikhnytsky, Engineer-physicist, Ya. Kmetyuk,
Head of All-Ukrainian center for radiosurgery, Clinical Hospital "Feofaniya"

RADIATION SAFETY ASPECTS DURING 11-MEV MEDICAL CYCLOTRON OPERATION AND MAINTENANCE

The paper brings up the question of radiation safety aspects dealing with exploitation of cyclotron Eclipse RD (Siemens), that is used for positron-emission tomography with fluorodeoxyglucose (^{18}F-FDG). The main sources of radiation exposure and the efficiency of a cyclotron shielding were analyzed. The dose rates were measured from the activated details and wastes and the effective dose to personnel, performing operation and technical support of a cyclotron was estimated with the help of electronic personnel dosimeters EPD Mk2+ and thermoluminiscence dosimeters TLD Harshaw 100.

***Keywords:** positron-emission tomography, fluorodeoxyglucose, cyclotron, radiation safety, effective dose.*

Introduction. Positron-emission tomography (PET) plays a crucial role in cancer diagnostics and can give information about the location of neoplasm and metastases, the intensity of metabolism and allows to estimate the efficiency of performed treatment [4]. PET requires radioactive tracers, and in this connection the low energy cyclotrons (up to 20 MeV) have found widespread applications in nuclear medicine for tracer production technologies [2]. The most commonly used PET radioisotopes (^{11}C, ^{13}N, ^{15}O, ^{18}F) can be produced through the proton induced reactions, such as (p,n) and (p,a). It is obvious, that the usage of cyclotrons leads to radiation exposure, caused by prompt radiation, produced tracer and induced activity. Moreover, in most cases cyclotron maintenance requires handling of radioactive components and wastes. Therefore special attention should be paid to the radiation safety aspects, providing additional shielding and dose control for personnel, who perform cyclotron operation and technical support. Besides, the analysis of the dose values enables to make a conclusion about the achieved radiation safety conditions and implementation of new safe measures, directed at a minimization of radiation exposure to personnel according to the ALARA principle.

F-18 production. PET-Cyclotrons produce different isotopes through the proton induced reactions, shown in table 1. For the different isotopes different types of targets are used (gas and liquid), and they have special properties, that ensures effective tracer yield in a harsh irradiation conditions.

Table 1

PET tracers, produced by medical cyclotrons

Product	Target Type	Half-life, min	Reaction
^{18}F	Liquid	110	$^{18}O(p,n)^{18}F$
^{11}C	Gas	20	$^{14}N(p,\alpha)^{11}C$
^{13}N	Liquid	10	$^{16}O(p,\alpha)^{13}N$
^{15}O	Gas	2	$^{15}N(p,n)^{15}O$

In All-Ukrainian center for radiosurgery of the Clinical Hospital "Feofaniya" the fluorodeoxyglucose (FDG) production technology was successfully implemented using self-shielded Siemens cyclotron Eclipse RD [1]. The self-shielding consists of concrete, borated polyethylene and lead, ensuring good radiation protection from neutrons and gamma rays. For ^{18}F production the enriched water with ^{18}O 98% enrichment and 1.2 ml volume is loaded to a target and due to $^{18}O(p,n)^{18}F$ nuclear reaction isotope ^{18}F is produced. For this production technology the liquid target is used, shown in fig.1a. It consists of silver target body, collimator and target window, made of Havar alloy [5], which is pressure and temperature resistant (melting point for Havar is 1753 K). During bombardment the target body and Havar window are cooled by water and helium systems respectively (fig. 1b. demonstrates target working conditions during irradiation). The beam extraction is performed through the 25 μm aluminum vacuum window, behind which a target is installed.

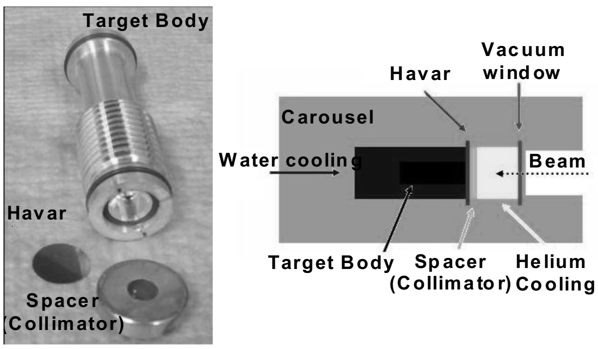

Fig. 1. ^{18}O liquid target:
a) construction b) irradiation conditions

The tracer yield decreases with time, which is caused by target deterioration during irradiation. Therefore the target and its components must be cleaned and replaced periodically. Fig. 2 demonstrates the ^{18}F tracer yield depending on a target usage. These data were obtained after 150 production runs without target rinse, and it should be note that with assumption of 4 working days/week and 1 hour/day production, the target lifetime of 1950 μAh will be reached after 3 months.

Radiation exposure and dose rate measurements. Cyclotron exploitation is accompanied by several sources of radiation, that cause additional exposure to personnel: prompt gamma rays and neutrons, produced tracer and induced activity of a cyclotron components. The prompt radiation exists only during irradiation and the greater part of it is absorbed by the cyclotron self-shielding. The dose rate on shielding surface during irradiation is 15 μSv/h for neutrons and 75 μSv/h for gamma rays respectively. The working place is located in the control room, where dose rate does not exceed 0.3 μSv/h.

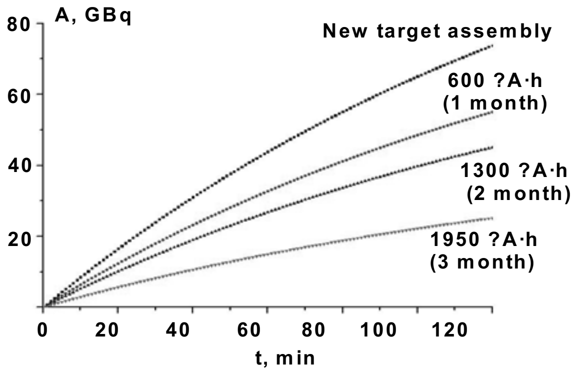

Fig. 2. Tracer yield dependence on a target usage

Table 2

Dose rates from vacuum window, target and its components

Element	Usage, mkA·h	Time after last bombardment, hours	Dose rate at 0.1m mSv/h
Target body	5210	60	0.14
Collimator (spacer)	5210	60	0.05
Havar foil	1950	60	5.42
Vacuum window	3540	60	2.52

After bombardment and tracer delivery to the lab, the relicts of produced tracer and induced activity become as the main sources of radiation. The shielding fully absorbs this radiation, but when the shield is open the dose rate near the target module can be very high (>15 mSv/h), and hence for technical maintenance it is necessary to wait at least for a one day for short-lived radionuclide decay.

The dose rates from different target components, measured after 60 hours from last bombardment are shown in table 2. The highest dose rate was measued from Havar window (about 5 mSv/h). Apart from the Havar foil long-lived isotopes are also induced in other target components and vacuum window, where dose rate can be up to 2.5 mSv/h. The technical maintenance of a cyclotron is performed by engineer-physicist and taking into account these dose rates, the effective dose to engineer is mostly caused by the actions, to be done in a close proximity to the target module (these works include target replacement, extractor replacement, ion source maintenance, vacuum window replacement and other). Regardless of type of work, almost all of them include 3 steps, mixed with exposure: there are demounting and installation, transportation and handling of radioactive parts of a cyclotron. Each of these steps must be executed using different types of shielding, such as lead screen, lead containers and fume hood with lead shielding and leadglass window for wastes handling. Activated details handling must be done very carefully using tweezers and after usage they should be enclosed in a special storage for farther decay.

Effective doses and data analysis. The yearly effective dose to engineer depends on the number of works, that should be done during a year. Since the irradiated target is the most activated detail, its maintenance forms the bigger part of dose. The average target lifetime appeared to be 1950 μAh (3months), so there are minimum 4 target replacement actions per year, excluding periodic target leakages and blowing of vacuum window. Table 3 shows the type and number of technical works, that were done in 2013 and corresponding effective doses to engineer, measured with the help of EPD MK2+ and TLD Harshaw 100 dosimeters. There were 6 target rebuilds, 1 extractor and cathodes replacement and 2 vacuum window replacements.

Table 3

Doses to engineer-physicist for different types of actions (10.01.13–26.12.13; 150 productions)

Type of work	Dose/action, μSv and number of actions (EPD Mk2+ measurements)	Effective dose, mSv/year (TLD measurements)	
Target rebuild	0.152 (6)	-	
Extractor replacement	0.075 (1)	-	
Cathodes of ion source replacement	0.063 (1)	-	
Vacuum window replacement	0.078 (2)	-	
SUM	**1.206**	**1.06**	**0.85** [3]

For the works, presented in table 3, the sum effective dose for EPD measurements is 1.206 mSv/year, and almost 80% of it goes from the target rebuild actions. For TLD measurements dose value is slightly lower: our results give 1.06 mSv, and in the Department of Nuclear Medicine of All india institute of medical Sciences, where the same cyclotron with the same parameters is used, the effective dose to engineer is 0.85 mSv/year [3]. Summarizing these data it is clear that all doses are considerably lower than dose limits, adopted by International Commission of Radiological Protection (ICRP) [6] and the average dose is about 1 mSv/year, which is comparable with the average background dose per year.

Conclusions. The radiation safety aspects during cyclotron exploitation were considered and the main sources of radiation exposure were analyzed. The dose rate measurements were performed and the effective dose to engineer, occupied with tracer production and technical maintenance was determined using EPD Mk2+ and TLD Harshaw 100 dosimeters.

One of the ways to get higher radiation doses is the increment of production runs, which leads to faster target degradation and therefore to bigger number of works. Since April, 2014, Hospital has started tracer productions not only for own, but also for external needs, and now production intensity increased twice. In these conditions the effective dose is expected to be 2.4 mSv/year, and even in this case the effective dose is sufficiently low and does not exceed 15% of dose limits, adopted by ICRP. So, it can be concluded, that providing good shielding and organization of work, the usage of low energy cyclotrons can be absolutely safe and secure.

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Submitted on 06.10.14

Бондар Б., інженер-радіофізик, клінічна лікарня "Феофанія";
каф. ядерної фізики, фізичний факультет, Київський національний університет імені Тараса Шевченка
Міхницький І., інженер-радіофізик,
Кметюк Я., керівник Всеукраїнського центру радіохірургії
Клінічна лікарня "Феофанія"

РАДІАЦІЙНА БЕЗПЕКА ПРИ РОБОТІ ТА ТЕХНІЧНОМУ ОБСЛУГОВУВАННІ 11-МЕВ МЕДИЧНОГО ЦИКЛОТРОНУ

В роботі висвітлюються основні питання радіаційної безпеки при експлуатації циклотрону Eclipse RD (Siemens), що використовується для позитронно-емісійної томографії з фтордезоксиглюкозою (ФДГ). Проаналізовано основні джерела іонізуючого випромінювання та ефективність власного захисту циклотрону. Проведені вимірювання потужностей доз від активованих деталей та радіоактивних відходів, оцінено ефективні дози персоналу з використанням електронних індивідуальних дозиметрів EPD Mk2+ та термолюмінесцентних дозиметрів Harshaw 100.

Ключові слова: *позитронно-емісійна томографія, фтордезоксиглюкоза, циклотрон, радіаційна безпека, ефективна доза.*

Бондар Б., инженер-радиофизик, клиническая больница "Феофания";
каф. ядерной физики, физический факультет, Киевский национальный университет имени Тараса Шевченко
Михницкий И., инженер-радиофизик,
Кметюк Я., руководитель Всеукраинского центра радиохирургии,
Клиническая больница "Феофания"

РАДИАЦИОННАЯ БЕЗОПАСНОСТЬ ПРИ РАБОТЕ И ТЕХНИЧЕСКОМ ОБСЛУЖИВАНИИ 11-МЕВ МЕДИЦИНСКОГО ЦИКЛОТРОНА

В работе приведены вопросы радиационной безопасности при эксплуатации циклотрона Eclipse RD (Siemens), который используется для позитронно-эмисионной томографии с фтордезоксиглюкозой (ФДГ). Проанализированы основные источники излучения и эффективность собственной защиты циклотрона. Проведены измерения мощностей доз от активированных деталей и радиоактивных отходов, а так же сделана оценка эффективных доз персонала с использованием электронных индивидуальных дозиметров EPD Mk2+ и термолюминесцентных дозиметров Harshaw 100.

Ключевые слова: *позитронно-эмисионная томография, фтордезоксиглюкоза, циклотрон, радиационная безопасность, эффективная доза.*