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DEVICE FOR FAST INTERRUPTION OF ACCELERATED ION BEAM AT DC-60 AND IC-100 CYCLOTRONS

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To study the optical properties of irradiated solids at the early stages of defect structure formation, there is a need to improve the time resolution of the recorded ionoluminescence and to record particles interacting with the sample with a smaller energy spread. The article describes the developed system of a fast beam chopper, which is based on deflection plates placed in the channel of the axial injection of an accelerator, immediately before the injection of the ion beam into the magnetic resonance system of the accelerator. Chopper affects the constant flow of ions in the axial injection, obtained from the ion source and injected into the accelerator and deflects it with a frequency necessary to form the required number of bunches at the exit of the accelerator. Chopper allows to obtain a beam of charged particles with different time parameters on the DC-60 and IC-100 accelerator complexes, the resonance systems of which operate in the frequency range from 11 MHz to 22 MHz and, when accelerating ions, produce particle flows at the accelerator output, grouped into bunches with a duration of about ~2…5 ns and a repetition period of ~90…45 ns. This chopper uses a fast switch of high voltage supplied to the deflection plates, at which the ion flow is deflected at the right time from injection into the accelerator, thereby ensuring effective rarefaction of the number of bunches and, accordingly, the ion flow from 100% to 1%, down to single bunches.

Keywords: *cyclotron; chopper; interrupter; high voltage switch; ionoluminescence.*

INTRODUCTION

Experiments to study the properties of irradiated materials in real-time, or in-situ, are among the most informative in the radiation physics of solids. Such works include studies of the spectral composition and kinetics of luminescence generated by high-energy heavy charged particles – ionoluminescence (IL) [1]. The IL method allows studying processes associated with defect development in-situ, obtaining information from a depth of up to several micrometers at ion energies of more than several MeV [1], as well as identifying impurities in crystals [2], indicating implantation defects and phase transitions [3]. Experiments on ionoluminescence have already been conducted at the DC-60 and IC-100 accelerators, for example, on the study of radiation defects in Al_2O_3 [4] and LiF using IL [5]. This paper demonstrates the possibility of using a chopper for research in the field of ionoluminescence and radiation materials science at the DC-60 and IC-100 accelerators with improved beam time characteristics that were previously unavailable. The DC-60 accelerator allows researchers to produce ion beams from Li to Xe with the ion energy starting from 0.35 up to 1.75 MeV/nucleon [6]. A chopper (from the English "chopper" – interrupter) is a device for fast interruption of the particle beam [7]. Choppers are used to separate individual bunches from the beam for purposes such as beam intensity adjustment, radioisotope research, and time-of-flight measurements of protons and neutrons [7–10]. Changes in the ionoluminescence spectra and their intensity result from processes occurring in a broad time range, from the relaxation of electron excitations to the formation of complexes of radiation defects, such as color centers [4, 11]. Registration of time characteristics in the picosecond range assumes excitation of optical radiation by single ions, as, for example, in [12, 13] due to the absence of accelerators producing ultrashort pulses of charged particles. To analyze luminescence decay curves at large time lengths, pulses (bunches) of particles with a duration of units or tens of nanoseconds [4], as well as groups of such pulses can be used, provided that the characteristic luminescence time significantly exceeds the duration of the bunch/group of bunches. The formation of periodic excitation pulses of a given duration can be implemented using an ion beam chopper. This makes it possible to study the kinetics of IL with the required time resolution in various time intervals [4]. In addition, the chopper can also be used to interrupt the ion flow in experiments on studying the processes of phosphorescence (afterglow) caused by the action of accelerated ion beams [14, 15]. It should be noted that the results of such studies of chopper application for IL are presented in the literature by a very limited number of publications.

This work is dedicated to the development of a device for fast interruption of the ion flow at the DC-60 and IC-100 cyclotrons for applied research [16, 17], as well as a detector of starting signals in the experiments to study the kinetics of high-energy ionoluminescence of crystals such as Al_2O_3, $MgAl_2O_4$ and MgO.

METHODS

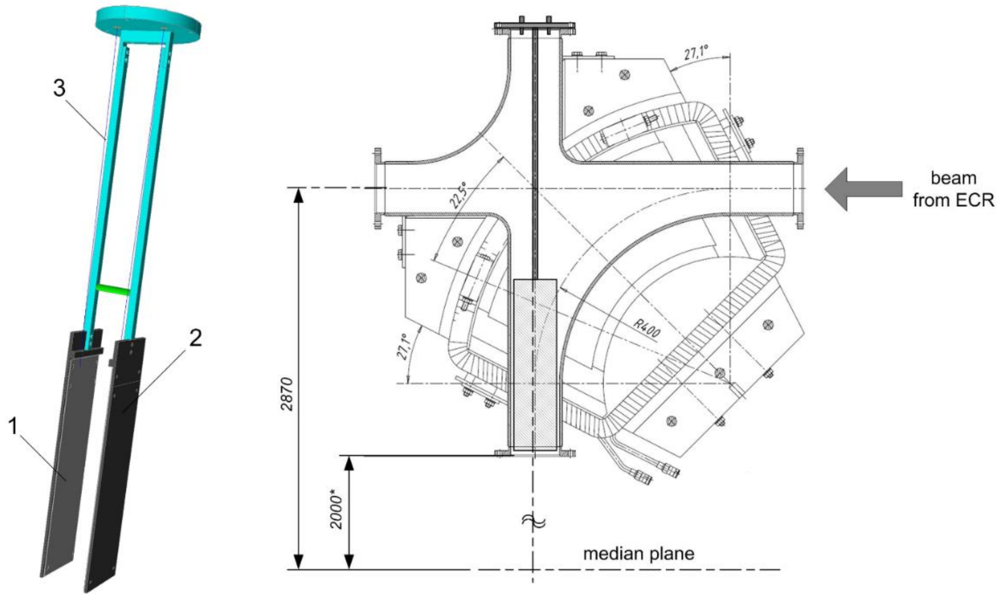
The chopper was tested on the DC-60 heavy ion accelerator at the Astana branch of the Institute of Nuclear Physics (Astana, Kazakhstan) and IC-100 heavy ion accelerator (Joint Institute for Nuclear Research, Dubna, Russia). A microchannel plate (MCP) detector was used for generating starting signals in the studies of decay curves of luminescence stimulated by single high-energy ions. Signals from a microchannel plate (MCP) detector were measured using the Tektronix MD03102 mixed domain oscilloscope. The working principle of the developed chopper and detector system based on MCP is discussed in further detail in the following sections.

RESULTS AND DISCUSSION

Device for fast interruption of the beam

The chopper consists of two plane-parallel plates installed in the axial injection channel of the cyclotron inside the vacuum volume of the IM90 bending magnet (Figures 1a, 1b), directing the ion beam from the ECR (Electron Cyclotron Resonance) source channel to the electrostatic inflector in the accelerator chamber of DC-60 or IC-100. These cyclotrons have similar axial injection elements, in particular the bending analyzing magnet, as well as a similar structure of axial injection of the ion beam.

The beam interruption required to form pulsed ion beams in specified time intervals occurs due to its deflection in the electric field of the chopper. The functional diagram of the chopper control system is shown in Figure 2. It includes a control device, which, depending on the operating mode and degree of beam rarefaction specified by the operator, supplies high-voltage pulses (HV pulse) to the chopper plates. The control device is matched with the cyclotron resonance system using a signal generator. The key element of the system – the control device – includes a high-voltage DC power source and a high-voltage pulse switch.



a) b)

Figure 1. Diagram of the chopper: (a) design: 1 – deflecting plate, 2 – isolator, 3 – power cord; (b) installation in the channel of axial injection of the cyclotron

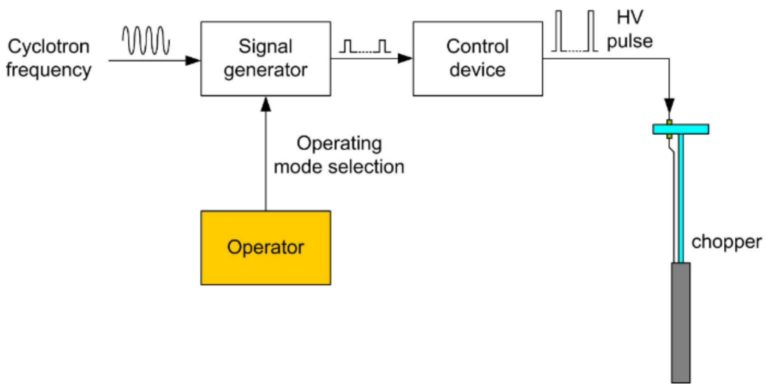


Figure 2. Functional diagram of the chopper control

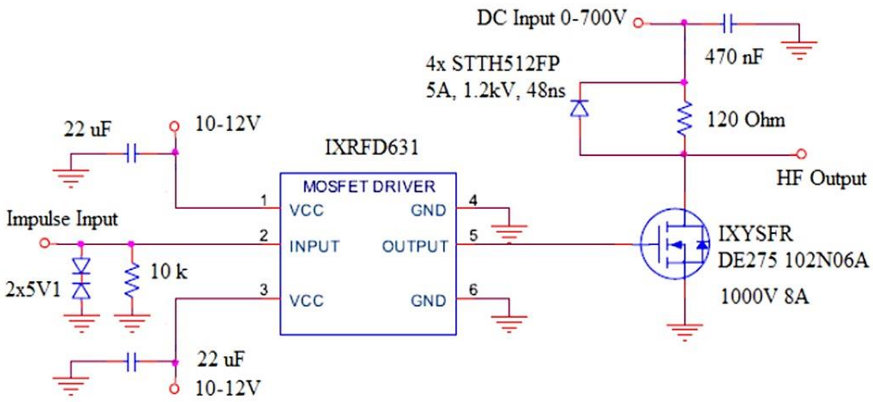


Figure 3. Circuit diagram of the high voltage pulse switch

The high voltage switch is based on the RF Power MOSFET DE275-102N06A transistor controlled by the IXRFD631 driver [18], shown in Figure 3. It can generate high voltage pulses with an amplitude of up to 500 V. The time of the control signal coming from the master signal generator to the fast control transistor of the chopper control device for its short-term opening is determined as:

$$t_{ONDLY} + t_R + t_{OFFDLY} + t_F = 56 \text{ (ns)} \quad (1)$$

Here t_{ONDLY} is the turn-on signal propagation delay (ns), t_R is the signal rise time (ns), t_{OFFDLY} is the turn-off signal propagation delay (ns), t_F is the signal fall time (ns).

The minimum duration of the control signal of the driver itself $PW_{MIN} = 8$ ns can be neglected, since it is much less than the required duration of the general control signal and less than the bunch repetition period. The opening time of the DE275-102N06A control transistor [19] is defined in a similar way:

$$t_{d(on)} + t_{on} + t_{d(off)} + t_{off} = 14 \text{ (ns)}, \quad (2)$$

where $t_{d(on)}$ is the turn-on signal propagation delay (ns), t_{on} is the signal turn-on time (ns), $t_{d(off)}$ is the turn-off signal propagation delay (ns), t_{off} is the signal turn-off time (ns). Thus, the delay time of the chopper control device electronics operation is estimated at 56 + 14 = 70 ns. This is comparable with the period of the cyclotron frequency, for example ~60 ns (16.650 MHz) of the DC-60 cyclotron or ~44 ns (22.870 MHz) of the IC-100 cyclotron. Let us consider whether it is possible with such a duration of the control signal to isolate individual bunches of ion beams, such as krypton $^{84}Kr^{15+}$ and xenon $^{132}Xe^{22+}$.

Therefore, for example, in the operating range of the parameters of the cyclotron ECR ion source at an accelerating voltage of $U_{ECR} = 17$ kV for xenon-132 ions (mass $m = 131.9$ atomic mass units (amu)) with a charge $Z = 22+$, which corresponds to their initial kinetic energy $T = 373.5$ keV, the ion velocity v_{x0} in the axial injection channel will be:

$$v_{x0} = \sqrt{\frac{2ZeU_{ECR}}{m}} = 7.392 \cdot 10^5 \text{ m/s}. \quad (3)$$

At a chopper operating voltage of $U_{ch} = 300$ V with a length of deflecting elements $l = 350$ mm, installed at a distance of $d = 80$ mm, the maximum deviation Z_{max} of the xenon ion trajectory can be calculated using equations of motion for non-relativistic particles and electrostatic force from the deflecting elements:

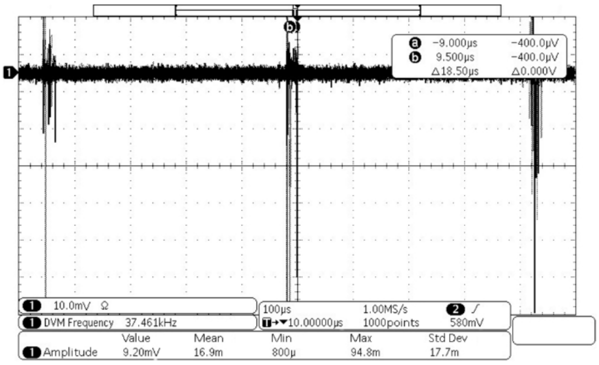
$$Z_{max} = \frac{ZeE_z l^2}{2mv_{x0}^2} = 6.8 \text{ mm}, \quad (4)$$

where E_z is the electric field strength between the chopper's plates, which corresponds to a maximum angle of departure of 2.2°. Considering the length of the "flight base" – the length of the particle path from the chopper to the inflector installed in the median plane of the main cyclotron magnet (Figure 1b) – 2.4 m, the maximum deflection of the ion beam will be more than 86 mm, which ensures a total deflection of the particle flow in the injection channel from entering the inflector input window equal to 10 mm, thereby guaranteeing the formation of the required time intervals of ion flows.

The parameters for krypton-84 ions with charge $Z = 15+$ were obtained in a similar manner, corresponding to the initial kinetic energy $T = 254.7$ keV, velocity $7.653 \cdot 10^5$ m/s, maximum trajectory deviation in the chopper of 6.8 mm, departure angle of 2.2°, maximum ion beam deviation on the flight path of more than 86 mm.

The developed device was tested in ionoluminescence experiments on the DC-60 and IC-100 accelerators. The measurements were carried out on spinel ($MgAl_2O_4$) single crystal samples with different temporal structures (beam rarefaction levels), varied using a chopper. Figures 4a–c show, as an example, oscillograms of signals from a microchannel plate (MCP) detector generating start pulses when measuring luminescence decay curves for the transmission of 5%, 15%, and 50% of bunches of a 156 MeV xenon ion beam on the IC-100 cyclotron. The signals were recorded with an MD03102 digital oscilloscope. The control signal to the chopper control device was supplied from an AFG3152C type generator. Therefore, to transmit 5% of the bunches, the duration of the control signal was set to 4.6 μs.

The operating mode was selected so that the chopper was initially in the “closed” state, i.e. high voltage was applied to it, and when the control signal was sent, the chopper “opened” for subsequent acceleration. The chopper operating period, i.e. the control signal repetition period was chosen equal to 2.287 kHz (1:10000 of cyclotron frequency of 22.870 MHz, when conducting a series of experiments on the IC-100 cyclotron). Therefore, for transmitting 5% of the beam (a total of about 500 bunches out of 10000), the duration of the packet of pulses registered with the MCP of about 18.5 μs was obtained (the duration between markers a and b in Figure 4a).



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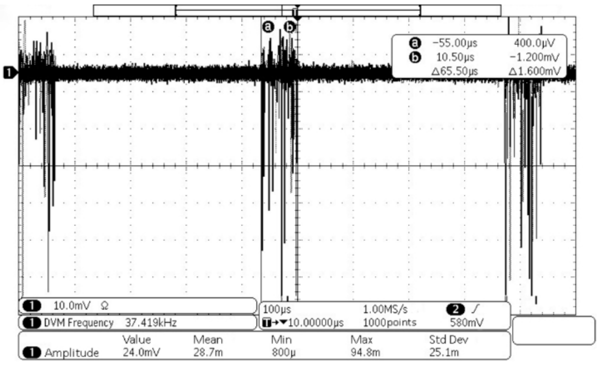

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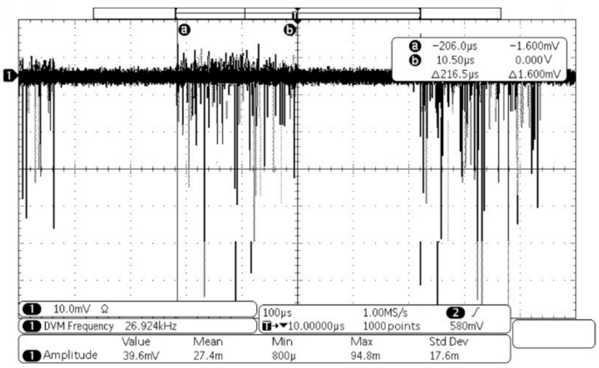
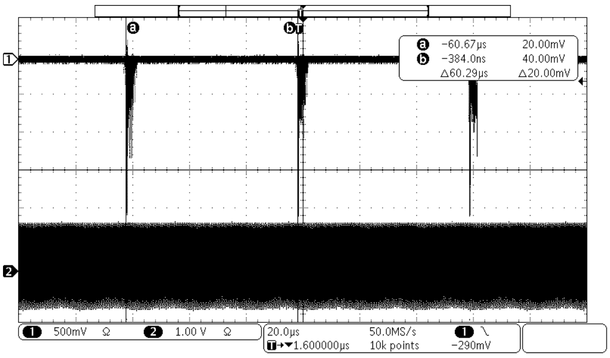


c)

Figure 4. Temporal structure of the Xe ion beam at 5% (a), 15% (b) and 50% (c) bunch transmission at the IC-100 accelerator

With such a packet duration, the calculated number of bunches is 423, which corresponds to about 5% of the total ion flow. Figures 4b and 4c show similar oscillograms for transmitting 15% and 50% of the beam bunches, with a control signal duration of 5.1 μs and 8.7 μs, respectively.

Similar measurements were carried out at the DC-60 cyclotron with similar equipment using a similar technique, except for the control signal generator. The control signal to the chopper control device was fed from a 33500B type generator. Figures 5a–b show, as an example, the oscillograms of signals when transmitting 5% of bunches of a beam of xenon ions with an energy of 231 MeV at the DC-60 cyclotron. The chopper operating frequency was chosen to be 16.650 kHz (1:1000 of the cyclotron frequency of 16.650 MHz when conducting a series of experiments at the DC-60 cyclotron), while corresponding period was around 60.29 μs as shown between markers a and b in Figure 5a. To transmit 5% of the bunches, the control signal duration was set to 3.4 μs, so with a limited beam transmission (only about 50 bunches out of 1000), the pulse packet duration recorded by the detector was about 2.95 μs (the duration between markers a and b in Figure 5b). With this packet duration, the calculated number of bunches is 49, which corresponds to about 5% of the total ion flux.



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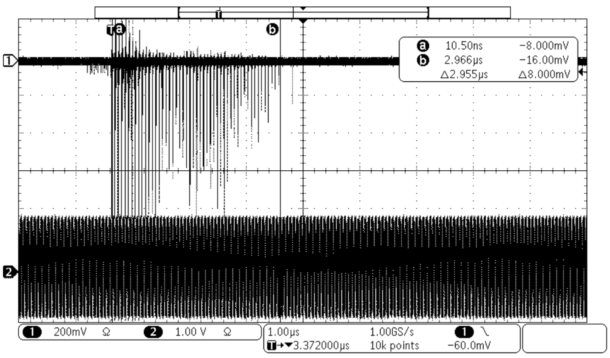
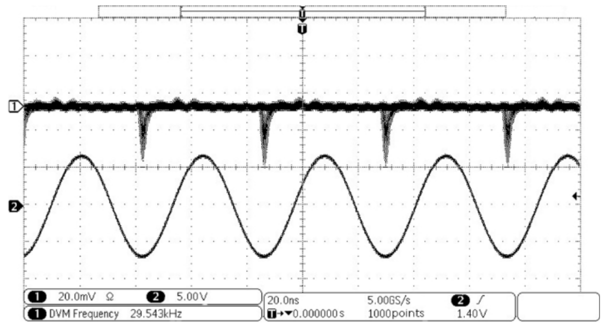


b)

Figure 5. Temporal structure of the Xe ion beam with 5% bunch transmission, at the DC-60 accelerator. Here: a) signal with a chopper operating period, b) pulse packet duration, recorded by the MCP detector. Marker “1” is the signal from the detector, marker “2” is the sinusoidal signal of the cyclotron frequency



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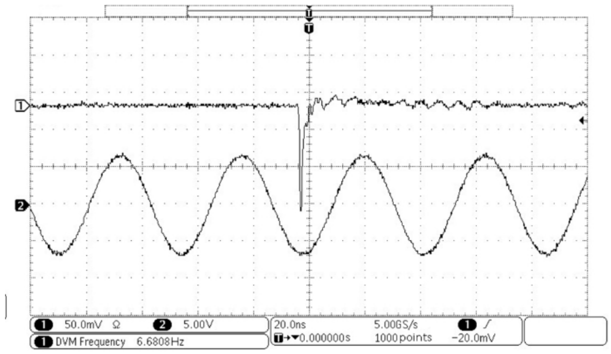


b)

Figure 6. Registration of signals: (a) without a chopper and (b) with a chopper when isolating a single bunch of the beam at IC-100. The degree of rarefaction of the beam is 1%. Marker "1" is the signal from the detector, marker "2" is the sinusoidal signal of the cyclotron frequency.

An example of oscillograms demonstrating two modes of operation of the chopper with the transmission of all bunches and a single bunch of the beam at the IC-100 accelerator is shown in Figure 6. The signal of the cyclotron frequency of 22.870 MHz (sinusoid) of the resonant system of the accelerator is also shown here below with a marker "2". The scale interval (Figure 6a, b) for the duration of the signal is 20 ns, therefore, the signal from one bunch relative to the cyclotron frequency corresponding to a period of 43.4 ns is visible in the figure.

Figure 7 shows an oscillogram demonstrating the chopper operation mode with the transmission of one bunch of the beam at the DC-60 accelerator. The marker "2" also shows the signal of the cyclotron frequency of 16.650 MHz (sinusoid) of the resonance system of the DC-60 accelerator. The scale interval (Figure 7) for the signal duration is 40 ns, therefore the figure shows the signal from one bunch relative to the cyclotron frequency corresponding to a period of 60 ns, with a beam rarefaction degree of no more than 1.5%.

The above data demonstrate the capabilities of the chopper to change the temporal structure of a high-energy ion beam and to perform measurements using both single bunches and single ions if the particle flow density is much lower than the bunch frequency. Chopper allowed obtaining a beam of ions with different time parameters on the DC-60 and IC-100 accelerator complexes, the resonance systems of which operate in the frequency range from 11 MHz to 22 MHz and, when accelerating ions, produce particle flows at the accelerator output, grouped into bunches with a duration of about ~2…5 ns and a repetition period of ~90…45 ns.

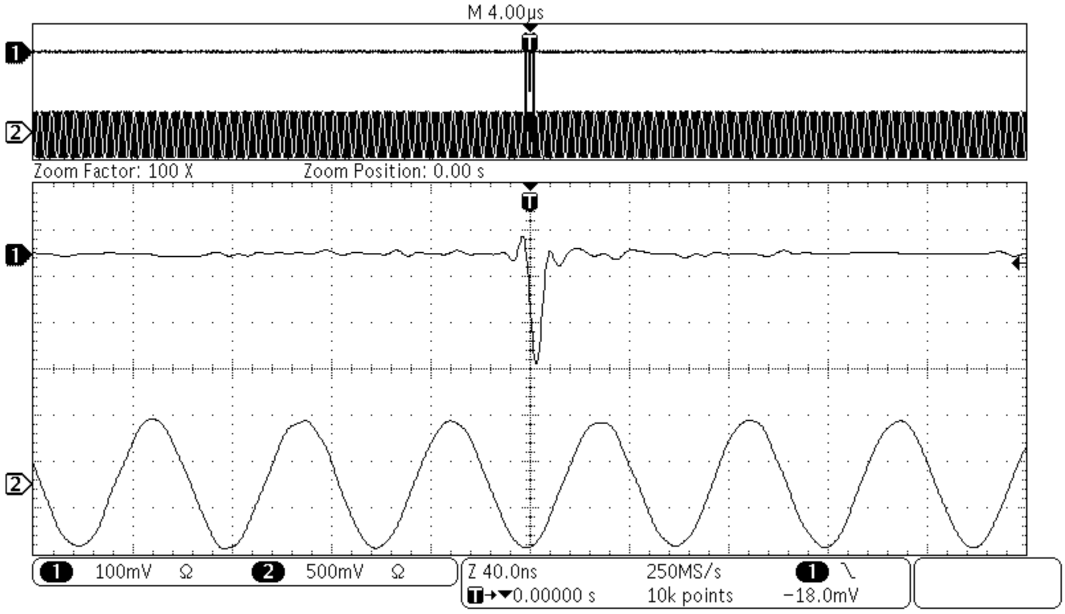
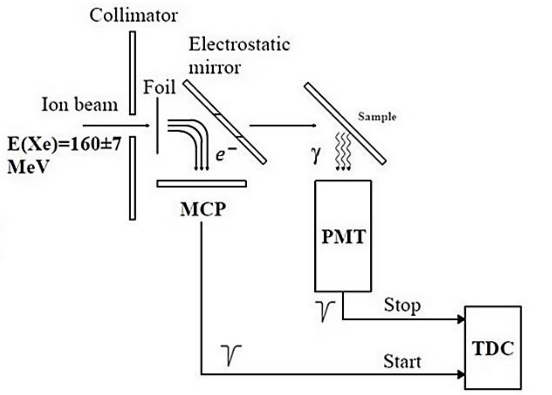


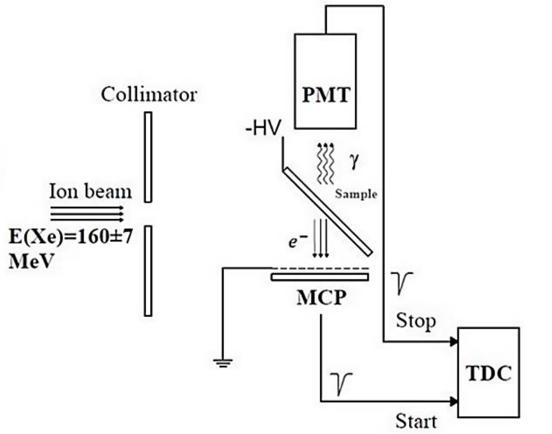
Figure 7. Signal registration with a chopper when isolating one bunch of the beam at the DC-60 accelerator. The degree of beam rarefaction is no more than 1.5%. Marker "1" is the signal from the detector, marker "2" is the sinusoidal signal of the cyclotron frequency. The range of the signal registration period is additionally shown at the top, with a display of 100 times magnification, i.e. one bunch in a period of about 4 µs

Detector of starting signals in ionoluminescence experiments

This section describes a device for generating starting signals in the studies of curves of luminescence decay stimulated by single high-energy ions. In all previously conducted experiments, detectors based on the MCP [13, 20] were used for this purpose, located at some distance in front of the sample (Figure 8a). The signal in such detectors is formed due to electron emission from the carbon foil, which occurs when high-energy ions pass through it. As a result, the function of instrumental (time) resolution, in addition to the parameters of the detectors and electronics, is also determined by the ion dispersion by energy due to scattering on the foil in addition to that already present in the original beam, which, as a rule, is not less than 1%, which is typical for all cyclic accelerators. The electrons emitted from the foil are detected by the MCP, which generates the "start" signal for launching the luminescence lifetime measurements. Photons produced from the sample irradiated with ions are detected by a photomultiplier (PMT) and generate the "stop" signal. A TimeHarp 260 time-correlated single photon counting board (TDC) is used to construct the curves of ionoluminescence decay.



a)



b)

Figure 8. Block diagram of a device for measuring luminescence decay curves during irradiation with single high-energy ions: a) design in previous experiments, b) proposed design

In the design that we have proposed (Figure 8b), the difference is that the emission of electrons from the surface of the irradiated sample, onto which a thin (20 nm) metal film is deposited by vacuum deposition, is used to generate starting pulses. A conductive layer with a thickness much smaller than the wavelength of radiation in the visible region, which has virtually no effect on the photon yield, is necessary to create a uniform electric field on the target surface and prevent charge accumulation in the dielectric. This method virtually eliminates the effect of ion energy dispersion on the measurement of luminescence decay curves. An important feature of the design is that both detectors, MCP and PMT, as well as the sample, are mounted on a single standard DN-100 vacuum flange, which allows experiments to be carried out on any accelerator in standard ion beam diagnostic blocks.

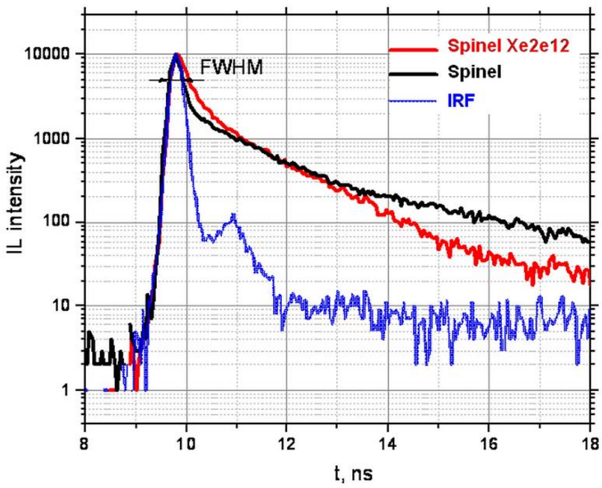


Figure 9. The time resolution function and luminescence decay curves of the initial and irradiated spinel. Measurements during irradiation with xenon ions (156 MeV). Ion flux density equals 10^6 $cm^{-2}s^{-1}$. FWHM = 250 ps

Figure 9 shows the time resolution function (IRF) measured on SiO_2 single crystals with a known decay time of excited states of less than 100 ps [21]. As can be seen, the full width at half maximum (FWHM), which is the instrumental resolution of the setup, is 250 ps, which allows us to study the decay kinetics of ionoluminescence starting from the subnanosecond range. The figure also shows the decay curves of luminescence stimulated by 156 MeV xenon ions obtained on the initial spinel crystals and samples pre-irradiated to a fluence of $2 \cdot 10^{12}$ cm^{-2} as an example. The data illustrate the effect of radiation damage created by high-energy xenon ions on the kinetics of radiative recombination of excited states in the ion trajectory region.

CONCLUSION

As a result, a device for fast interruption of ion flows on DC-60 and IC-100 cyclotrons with the same structure of axial injection of ion flow from ECR source into the working chamber of the accelerator has been developed and manufactured. During test experiments, the possibility of designing the chopper for obtaining sparse ion beams with different bunch filling factors, down to a single bunch, has been demonstrated. A new design of the start signal detector has been developed for studying the kinetics of luminescence generated by high-energy ions, based on the use of electron emission directly from the surface of the sample under study and providing a time resolution of at least 250 picoseconds. The presented methodological developments significantly expand the possibilities of studying the optical properties of irradiated solids at early stages of defect structure formation.

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DC-60 ЖӘНЕ IC-100 ЦИКЛОТРОНДАРЫНДАҒЫ ҮДЕТІЛГЕН ИОН АҒЫНЫН ТЕЗ ҮЗУГЕ АРНАЛҒАН ҚҰРЫЛҒЫ

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Сәулеленген қатты денелердің оптикалық қасиеттерін ақаулық құрылымның қалыптасуының бастапқы кезеңдерінде зерттеу үшін тіркелетін ионолюминесценцияның уақыт бойынша айыруды жақсарту және нысанамен әрекеттесетін бөлшектерді энергияның азырақ шашылымымен тіркеу қажет. Мақалада иондық шоқты үдеткіштің магниттік-резонансты жүйесіне айдау алдында үдеткіштің аксиалды инжекциясының арнасында орналастырылған ауытқытушы пластиналарға негізделген «чоппер» деп аталатын жылдам шоқты үзгіштің әзірленген жүйесі сипатталған. Чоппер ион көзінен алынған және үдеткішке айдалатын аксиалды инжекция арнасындағы иондардың тұрақты ағынына әсер етеді және оны үдеткіштің шығуында қажетті жиынтық («банч») санын алу үшін қажетті жиілікте ауытқытады. Чоппер резонанстық жүйелері 11 МГц-тен 22 МГц-ке дейінгі жиілік диапазонында жұмыс істейтін DC-60 және IC-100 үдеткіш кешендерінде әртүрлі уақыт параметрлері бар зарядталған бөлшектер шоғын алуға мүмкіндік береді, ал иондарды үдету кезінде ол үдеткіштің шығуында ұзақтығы шамамен ~2 нс және ~5 нс-қа тең және қайталану периоды ~90…45 нс-қа тең бөлшектер жиынтықтарына топтастырылған ағындарды жасайды. Бұл чопперде жоғары жылдамдықты ажыратып-қосқыш пайдалану арқылы ауытқытушы пластиналарға жоғары кернеу жеткізіліп, онда ион ағыны үдеткішке айдалудан қажетті сәтте ауытқиды, осылайша жиынтықтар санын, сәйкесінше ион ағынын 100%-дан 1%-ға дейін, бір жиынтыққа дейін тиімді сиретуді қамтамасыз етеді.

Түйін сөздер: *циклотрон; чоппер; үзгіш; жоғарывольтті ажыратып-қосқыш; ионолюминесценция.*

УСТРОЙСТВО БЫСТРОГО ПРЕРЫВАНИЯ ПОТОКА УСКОРЕННЫХ ИОНОВ НА ЦИКЛОТРОНАХ DC-60 И IC-100

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Для исследования оптических свойств облученных твердых тел на ранних стадиях образования дефектной структуры возникает необходимость улучшения временного разрешения регистрируемой ионолюминесценции и регистрации взаимодействующих с образцом частиц с меньшим разбросом энергий. В статье описывается разработанная система быстрого прерывателя пучка, именуемая «чоппер», в основе которой лежат отклоняющие пластины, размещаемые в канале аксиальной инжекции ускорителя, непосредственно перед инжекцией ионного пучка в магнитно-резонансную систему ускорителя. Чоппер влияет на постоянный поток ионов в аксиальной инжекции, получаемый из источника ионов и инжектируемый в ускоритель, и отклоняет его с частотой, необходимой для получения необходимого количества сгустков («банчей») на выходе из ускорителя. Чоппер позволяет получать пучок заряженных частиц с различными временными параметрами на ускорительных комплексах DC-60 и IC-100, резонансные системы которых работают в диапазоне частот от 11 МГц до 22 МГц, и при ускорении ионов создает на выходе ускорителя потоки частиц, сгруппированные в сгустки длительностью около ~2 …5 нс и с периодом повтора ~90…45 нс. В данном чоппере используется быстродействующий переключатель высокого напряжения, подаваемого на отклоняющие пластины, на которых поток ионов отклоняется в нужный момент от инжекции в ускоритель, тем самым обеспечивая эффективное разрежение количества сгустков, а соответственно и потока ионов от 100% до 1%, вплоть до одиночных сгустков.

Ключевые слова: *циклотрон; чоппер; прерыватель; высоковольтный переключатель; ионолюминесценция.*