in the beam. We mentioned a higher absorbed dose on 0.4% for the measurements with detector inside the beam.

Conclusions. Advantages of MMD allow to create a reliable radiation monitoring systems for radiation therapy applications. Their implementation will improve beam delivery to tumor tissue, fast imaging and evaluation of data, optimization of treatment regimes. Commercially available read-out systems can be applied to build high efficient monitoring system for hadron radiation therapy. MMD has shown reliable performance for online beam profile monitoring. Once calibrated, the detector could also be used for dose monitoring in real time. This is one of the main tasks for the further measurements.

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REFERENCE:

1. *Martinez-Rovira I.* Monte Carlo-based dose calculation engine for minibeam radiation therapy / *I. Martinez-Rovira, J. Sempau, Y. Prezado* // Physica Medica: European Journal of Medical Physics. – 2013. – Vol. 30. – Issue 1. – P. 57–62.
2. Micro-strip metal detector for the beam profile monitoring / *Pugatch V., Aushev V., Fedorovitch O.* et al. // Nuclear Instruments and Methods. – 2007. – Vol. A 581. – P. 531.
3. Metal Micro-detector TimePix imaging synchrotron radiation beams at the ESRF Bio-Medical Beamline ID17 / *Pugatch V., Campbell M., Chaus A.* et al. // Nuclear Instruments and Methods A. – 2012. – Vol. 682. – P. 8–11.

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МЕТАЛЕВІ МІКРО-ДЕТЕКТОРИ ДЛЯ ВІЗУАЛІЗАЦІЇ ТА МОНІТОРИНГУ ПРОФІЛЮ ПУЧКА В РАДІАЦІЙНІЙ ТЕРАПІЇ

Металеві мікро-детектори (ММД) розроблені в Інституті ядерних досліджень НАН України. В роботі представлені фізика та техніка таких детекторів для дозиметрії, реєстрації та візуалізації пучків заряджених частинок. Для забезпечення точного моніторингу профілю пучка виготовлений 128-канальний X-Y ММДд. Проведено тестові вимірювання з цим детектором для електронів з енергією 20 МеВ (Медична клініка "Інновація"), а також високоенергетичних адронних пучків (протони, іони ^{12}C та ^{16}O, Хайдельберг, Центр важко-іонної терапії). Результати цих досліджень обговорюються у роботі. Результати наших досліджень вказують на можливість застосування ММД в клінічній практиці.

Ключові слова: *металеві мікро-детектори, моніторинг профілю пучка, моніторинг дози онлайн, міні-пучкова променева терапія.*

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МЕТАЛЛИЧЕСКИЕ МИКРО-ДЕТЕКТОРЫ ДЛЯ ВИЗУАЛИЗАЦИИ И МОНИТОРИНГА ПРОФИЛЯ ПУЧКА В РАДИАЦИОННОЙ ТЕРАПИИ

Металлические микро-детекторы (ММД) разработаны в Институте ядерных исследований НАН Украины. В работе представлены физика и техника таких детекторов для дозиметрии, регистрации и визуализации пучков заряженных частиц. Для обеспечения точного мониторинга профиля пучка изготовлен 128-канальный X-Y ММДп. Проведены тестовые измерения с этим детектором для электронов с энергией 20 МеВ (Медицинская клиника "Инновация"), а также высокоэнергетических адронных пучков (протоны, ионы 12C и 16O, Хайдельберг, Центр тяжело-ионной терапии). Результаты этих исследований обсуждаются в данной работе. Результаты наших исследований свидетельствуют о возможности применения ММД в клинической практике.

Ключевые слова: *металлические микро-детекторы, мониторинг профиля пучка, мониторинг дозы онлайн, мини-пучковая лучевая терапия.*

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SELF-PHASE MODULATION OF LASER PULSE IN STRATIFIED SELF-FOCUSING MEDIUM

Self-phase modulation at quasi-stationary self-focusing in stratified Kerr liquid that is divided by an optically homogenous (non-scattering) layer has been considered. Instantaneous frequency of the laser radiation pulse at transition of the self-focusing area through a thin transparent layer is calculated. In addition, absorption of the light in the layer is taken into account.

The transition radiation on the layer (a glass partition or a similar structure), located in the self-focusing medium, has analogous characteristics with the radiation at the exit border of the medium. The frequency shift of the transition radiation, originated on the layer, is smaller than the shift of the laser radiation at the exit border of the medium. However, considering that the number of layers can be more than one, it could be concluded that introduction of the layers simplifies the experimental observation of the transition radiation and its usage.

Keywords: *laser, self-focusing, phase self-modulation, transition effect*

Introduction. Combination of Stimulated Raman Scattering (SRS) as an effective method of laser radiation frequency tuning [5], and self-focusing (SF) as a method of spatial scanning by powerful pulses of electromagnetic field at a velocity close to the speed of light [4], allows transforming the initial pulse of laser radiation into a random sequence of sub-pulses with a controlled duration and frequency of each sub-pulse [3]. To achieve this, the laser pulse has to be guided through a sample made of transverse layers of different SRS-active self-focusing materials with a specified thickness. However, implementation of this idea faces major physical challenges related with the effect of phase modulation on the laser radiation. This paper is dedicated to analyzing these physical challenges.

Phase self-modulation in self-focusing cell divided by a transparent layer. Let's consider the case of a thin non-absorbing layer, which is located in a self-focusing medium. We assume that this layer does not have a light field induced shift Δn and the value n_0 of its linear refractive index is approximately equal to the refractive index of SRS-active medium. Such situation can be achieved in a cell filled with self-focusing (Kerr) liquid, which contains thin optically transparent glass partition. Under such conditions, SF in Kerr medium occurs without dissipation of laser radiation in the layer.

The model proposed in [1] can be used to calculate the phase shift $\Delta\varphi$ of Gaussian pulse, with duration τ =1 ns and normalized power $\tilde{P} = P/P_{cr}$ (P_{cr} is a critical power of SF), at the exit from the medium with length L. This model takes into account alteration in time t, which occurs in the focal area position, and its geometrical dimensions depending on the radiation intensity. Self-induced phase shift was calculated using expression:

$$\Delta\varphi(t) = k_0\tilde{P}(t)\frac{(1.22\lambda_0)^2}{16n_0}\left(\int_0^{L_\ell} a_z^{-2}dz + \int_{L_\ell+\ell}^{L} a_z^{-2}dz\right), \qquad (1)$$

where $k_0 = 2\pi/\lambda_0$, λ_0 is a wave length of the excitation pulse in vacuum, L_ℓ is a distance between the entrance border of the cell and the thin layer of linear optical medium with thickness ℓ, a_z is a radius of the laser beam at longitudinal coordinate z. When calculating using expression (1), it is assumed that the beam propagates linearly across the thin layer of non-active medium, thus ℓ has to be adequate with a confocal parameter of the focal area. With initial radius of the entry beam a_0 =113 μm, minimum radius of the beam at the focal area a_f =5 μm, and λ_0 =0.69 μm, the focal area size changes from 14 mm to 0.7 mm, if $\tilde{P}$ varies in the range from $\tilde{P}_{\min} = 1.3$ to $\tilde{P}_{\max} = 3.6$.

Self-phase modulation induces the corresponding frequency shift of the laser pulse. Instantaneous frequency shift (in inverse centimeters) equals:

$$\Delta\nu(t) = -(2\pi c)^{-1}\partial(\Delta\varphi)/\partial t, \qquad (2)$$

where c is the speed of light in vacuum (in cm/sec).

The paper [2] states that when the self-focusing focal point crosses the border of two mediums (in [2] it is a "medium-vacuum" border), there the transition radiation appears at the frequency, which is shifted ($\sim\pm$ 140 cm^{-1}) relative to the excitation pulse of laser radiation. However, the transition radiation has a low (~0.5 %) spectral density in comparison with the spectral density of the initial pulse. Bigger spectral density of the transition radiation can be achieved at the moments of time, which correspond to the highest instantaneous power of the laser pulse. Therefore, the layer must be located near a stop point of the focal area.

Self-induced phase shift and instantaneous frequency shift, which appear during self-modulation of the laser pulse in toluene-filled cell with length L =30 cm and a thin transparent layer of non-active medium (ℓ =3 mm, L_ℓ =7 cm) near the stop point $z_{f\,\min}$ ≈6 cm (minimal distance of the self-focusing focal area at $\tilde{P}_{\max} = 3.6$), are shown in Fig. 1 and Fig. 2.

Self-induced phase shift (Fig. 1) has two local minimums near $t = 0$, which correspond to the moment when the focal area crosses the thin layer of non-active medium. When the layer thickness ℓ and distance L_ℓ increase, the width and the depth of the minimums also increase. Other parts of the plot shown in Fig. 1 look identical to the phase shift, which occurs under SF in the homogenous (without a partition) medium [1].

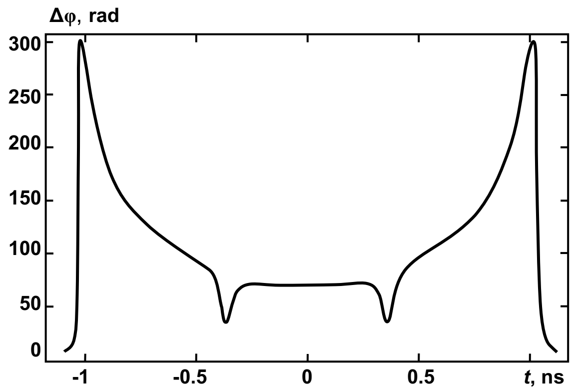

Fig. 1. The self-induced phase shift of the laser pulse at the exit of a toluene-filled cell divided by the transparent partition
(L =30 cm; L_ℓ =7 cm; ℓ =3 mm; τ =1 ns; $\tilde{P}_{\max}$ =3.6)

The transparent layer induces additional instantaneous frequency shift. The frequency shift is presented in Fig. 2.

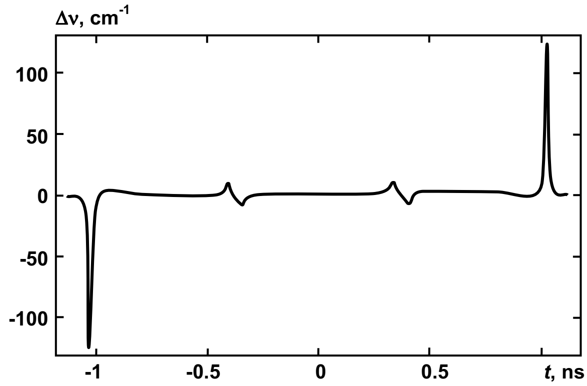

Fig. 2. The instantaneous frequency shift of the laser pulse at the exit of a toluene-filled cell divided by the transparent partition
(L =30 cm; L_ℓ =7 cm; ℓ =3 mm; τ =1 ns; $\tilde{P}_{\max}$ =3.6)

Phase self-modulation in self-focusing cell divided by an absorption layer. Presume that the self-focusing medium contain an infinitely thin absorbing partition with a dissipation factor k. When the beams pass through the partition under SF, the laser pulse loses a part of its energy $k = 1 - \left(\tilde{P}_\ell(t)/\tilde{P}(t)\right)$, where $\tilde{P}(t)$ and $\tilde{P}_\ell(t)$ are the power of laser pulse at a front and behind the partition.

The laser pulse passes the partition with different in time convergence angles and loses part of its energy. Therefore, the laser beam focuses at another point than without the absorbing partition. With usage of [1, 6], the dependence of the beam radius a_z from the coordinate z after the partition can be approximately expressed as:

$$a_z = \sqrt{a_\ell^2 \left| -\frac{z^2}{\gamma_\ell^2 a_\ell^4} + \left(1 + \left(\frac{da}{dz}\right)_{z=L_\ell} \frac{z}{a_\ell}\right)^2 \right|^{\mu_\ell/2} + a_f^2}\ , \qquad (3)$$

where a_ℓ is the beam radius at the partition, $\left(da_z/dz\right)_{z=L_\ell}$ is derivative at the partition, a_f is the minimum beam radius at the center of the focal area, γ_ℓ and μ_ℓ are parameters depended on the instantaneous power $\tilde{P}_\ell(t)$:

$$\gamma_\ell = 0.367 n_0 k_0 \Bigg/ \left[\left(\sqrt{\tilde{P}_\ell} - 0.852\right)^2 - 0.0219\right]^{0.5}, \qquad (4)$$

$$\mu_\ell = 2.9\tilde{P}_\ell^{-0.5} + \tilde{P}_\ell^{-1} + 1, \qquad (5)$$

Dependencies in Fig. 3 and Fig. 4 present the self-induced phase shift of the laser pulse and the instantaneous frequency, respectively, when the partition is located at distance L_ℓ =7 cm from the entrance of the cell and has the dissipation factor k =0.73.

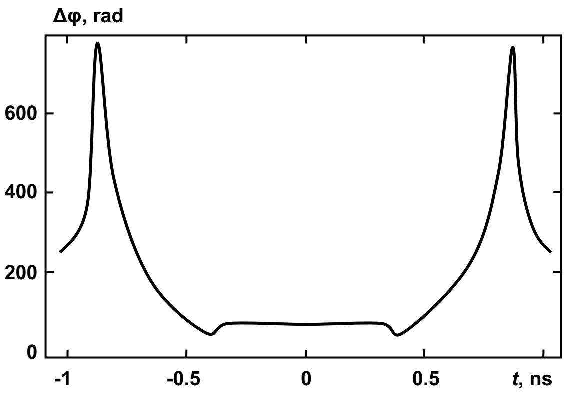

Fig. 3. The self-induced phase shift of the laser pulse at the exit of a toluene-filled cell divided by the thin absorbing partition
(L =30 cm; L_ℓ =7 cm; k = 0.73; τ =1 ns; $\tilde{P}_{max}$ =3.6)

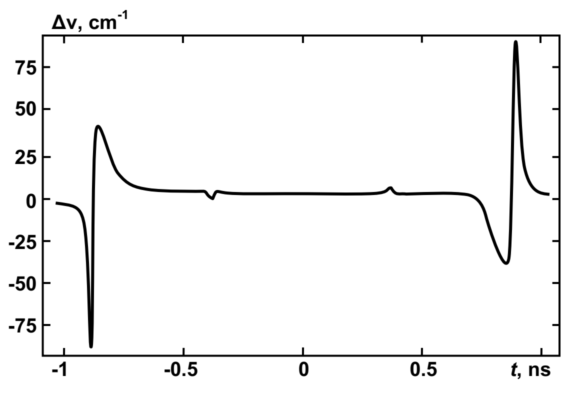

Fig. 4. The instantaneous frequency shift of the laser pulse at the exit of a toluene-filled cell divided by the thin absorbing partition
(L =30 cm; L_ℓ =7 cm; k = 0.73; τ =1 ns; $\tilde{P}_{max}$ =3.6)

The self-induced phase shift in Fig. 3 has two distinct maximums and minimums (the minimum at t =0 is almost unnoticeable).

A movement of the focal area behind the thin absorbing partition causes addition instantaneous frequency shift of laser pulse. Obviously, the plots in Fig. 2 and Fig. 4 have distinctive features.

In addition, it is possible to consider a local inhomogeneity of the "bubble" type, which in the simplest case is located on the axis of the laser beam path and has a radius, adequate with the geometrical dimensions of the focal area, but is smaller than the radius of the beam at the entrance of the medium. The beam appears "bubble" and dissipates during its intersection. The dissipation is as higher, as close the focal area is to the inhomogeneity. There comes a moment, when the inhomogeneity appears in a focal area. At that moment, when the focal area disappears for a short period, instantaneous frequency shift of laser pulse will be the same as at the exit of the cell.

Conclusions. In general practice, the layers combine properties of both described structures. This complicates the calculation of the laser pulse spectra. Nevertheless, the self-induced frequency shift of the laser pulse at the layers or local inhomogeneities in the self-focusing medium can be described by combining the two models described above.

There is small difference between the physical mechanisms related with the generation of the transition radiation in the transparent non-self-focusing layers, with definite width, and in the infinitely thin absorbing layers. In the first case, the radiation is generated due to the focal area entering and exiting the self-focusing medium near the layer. The second case takes place due to the change of the focal area length, when it crosses the absorbing thin layer.

The frequency shifts of the laser pulse originated at the layers are lower than the frequency shifts of the transition radiation originated from the border of the medium. However, there's observed a general trend of the radiation energy increase, which is almost inversed to the value of the frequency shift. Taking into account that the number of layers can be rather high, it could be considered that introduction of the layers greatly facilitates the experimental observation of the transition radiation. To some extent this can be compared with the transition radiation in the "foam" structures, which are used to increase the power of the transition and Cherenkov radiation in the applicable particle counters.

The stand-alone group of inhomogeneities, which lead to the generation of the intense transition radiation due to phase modulation, is inhomogeneities as scattering or absorbing "bubble", which size ~1 μm is close to the focal area diameter. Such inhomogeneities can occur naturally in medium. Despite the relatively small size of the inhomogeneities (this provides sufficient optical quality of the medium and makes possible the self-focusing in general) their role in the generation of the transition radiation can be exceptional. This is result of short-term collapse in formation of the focal area, similar to the intersection of the medium borders by the focal area.

Reference

1. *Borisenko A. D., Dudka S. O., Ivanisik A. I.* Quasi-stationary phase self-modulation of the laser pulses in Kerr liquids // Bulletin of T. Shevch. Nat. Univ. of Kyiv. Series: Physics and Mathematics.– 2003.– №.1.– P. 259–267.

2. *Dudka S. O., Ivanisik A. I., Konopatskiy A. V., Korotkov P. A.* Transition effect at the medium-vacuum interface under the self-phase modulation of a light pulse // Ukr. J. Phys.– 2006.– Vol. 51, №2.– P. 140–146.

3. *Ivanisik A. I., Maliy V. I., Ponezha G. V.* Stimulated Raman scattering in the self-focusing mediums: new methods of experimental research // Bulletin of T. Shevch. Nat. Univ. of Kyiv. Series: Physics and Mathematics.– 1997.– №.4.– P. 239–248.

4. Ivanisik A. I., Korotkov P. A., Ponezha G. V. Temporal dynamics of focal point location under self-focusing of nanosecond laser pulses // Ukr. J. of Phys. Opt.– 2013.– Vol. 15, №1.– P. 1–8.

5. Yao J., Wang Y. Nonlinear optics and solid-state lasers: advanced concepts, tuning-fundamentals and applications series.– Springer Series in Optical Sciences, 2012.– 688 p.

6. Shen Y. R. The Principles of nonlinear optics: translated from english.– M.: Nauka, 1989.– 560 p.

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ФАЗОВА САМОМОДУЛЯЦІЯ ЛАЗЕРНОГО ІМПУЛЬСУ В ШАРУВАТИХ САМОФОКУСУЮЧИХ СЕРЕДОВИЩАХ

У роботі розглянуто фазову самомодуляцію за квазістаціонарного самофокусування у шаруватій керрівській рідині, розділеній оптично однорідним (нерозсіюючим) прошарком. Обраховано миттєву частоту імпульсу лазерного випромінювання в момент перетину області самофокусування тонкого прозорого шару. Додатково враховано поглинання світла на шарі.

Перехідне випромінювання на прошарку (скляній пластинці або подібній структурі), розміщеному в самофокусуючому середовищі, має спільні характеристики з випромінюванням на виході із середовища. Зсув частоти перехідного випромінювання, що вийшло із шару, менший за зсув частоти лазерного випромінювання на виході із середовища. Враховуючи, що прошарків може бути кілька, виявляється, що введення шарів у середовище спрощує експериментальне дослідження та застосування перехідного випромінювання.

Ключові слова: *лазер, самофокусування, фазова самомодуляція, перехідний ефект*

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ФАЗОВАЯ САМОМОДУЛЯЦИЯ ЛАЗЕРНОГО ИМПУЛЬСА В СЛОИСТЫХ САМОФОКУСИРУЮЩИХ СРЕДАХ

В работе рассмотрена фазовая самомодуляция в случае квазистационарной самофокусировки в слоистой керровской жидкости, разделенной оптически однородным (нерассеивающим) слоем. Рассчитана мгновенная частота импульса лазерного излучения в момент перехода области самофокусировки через тонкий прозрачный слой. Дополнительно учтено поглощение света на слое.

Переходное излучение на слое (стеклянной пластинке или подобной структуре), размещенном в самофокусирующей среде, имеет общие характеристики с излучением на выходе из среды. Смещение частоты переходного излучения, вышедшего из слоя, меньше сдвига частоты лазерного излучения на выходе из среды. Учитывая, что слоев может быть несколько, оказывается, что введение слоев в среду упрощает экспериментальное исследование и применение переходного излучения.

Ключевые слова: *лазер, самофокусировка, фазовая самомодуляция, переходный эффект*

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STATISTICAL THEORY OF ELECTRO-DIFFUSION PROCESSES OF IONS INTERCALATION IN "ELECTROLYTE – ELECTRODE" SYSTEM

A statistical theory of classical-quantum description of electro-diffusion processes of intercalation in "electrolyte-electrode" system is proposed. Using the nonequilibrium statistical operator method the generalized transport equations of Nernst-Planck type for ions and electrons in the "electrolyte-electrode" system are obtained. These equations take into account time memory effects and spatial heterogeneity. A one-dimensional simplified model of intercalation of ions into the electrode structure with taking the dielectric polarization into account is proposed.

Keywords: *electrolyte, electrode, intercalation, nonequilibrium statistical operator .*

1. Introduction. Theoretical studies of electro-diffusion transport processes of ions and electrons in the "electrode-electrolyte" systems remain actual nowadays [6, 16, 19]. They are linked with a need to describe nonequilibrium processes of intercalation as well as to develop a theory suitable for practical application to predicting and controlling these processes. The difficulties in describing processes at electrode are first of all related with surface phenomena at electrolyte-electrode interface In this region, complicated processes of adsorption and diffusion take place which are connected with a problem of charge accumulation at battery electrodes. In the system "electrode (anode)-electrolyte-electrode (cathode)", the anode plays role of the source of both electrons, which move to cathode by the corresponding electric circle, and lithium ions in electrolyte. A cathode is typically a metallic system (nickel, for example) covered with active material containing carbon and in which lithium ions intercalate from the solution. Herewith, an important issue is the following one. The electrochemical processes in electrolyte solution can be described using methods of classical statistical mechanics, whereas in the region near the electrolyte-electrode interface and inside the electrodes, description of diffusion and intercalation processes should be implemented by means of the modern methods of quantum statistical physics. In this field, the electrochemical impendance studies [4, 1, 8] of electro-diffusion transport processes in Li-ion batteries [18, 9, 10] were carried out and intercalation/deintercalation processes were investigated using nonequilibrium thermodynamics [19, 9, 2, 17] The theoretical and experimental studies of chemical diffusion coefficient for lithium ions in intercalation