On Hard X-Rays Lasing from Interelectrodes Nanoparticle Ensembles of Vacuum Discharge

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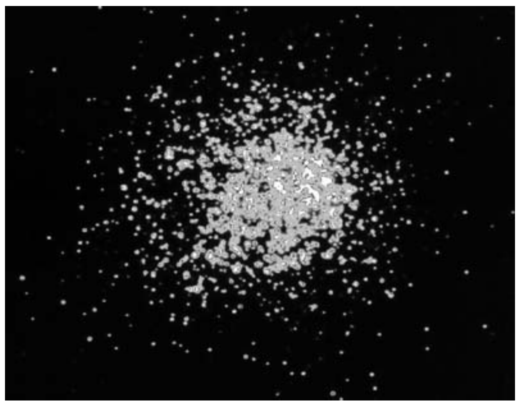
Abstract – High power density ensembles of clusters, creating as random interelectrode dusty-like media in low energy nanosecond vacuum discharges, are probable candidates for x-rays lasing media. Partial and essential x-ray trapping by ensembles as well as random laser behavior of potentially amplifying media of interelectrode complex plasma are considered. Last scheme with non-resonant feedback by energy have been suggested much earlier by V. Letokhov (1968), and the interest to random lasers is increased just at last decade and some realisations at visible spectra were obtained. In our case this scheme assumes the diffusion and partial "random walk" of photons inside of x-ray "ball" due to multiple scattering and reflecting in disordered media of cold and hot "grains" of any sizes. When the volume gain if available overcomes the surface losses, hard x-ray burst may take place (so called stochastic or *random laser*). The properties of ensembles with observed strong hard x-ray bursts which could be interpreted as amplified spontaneous emission (ASE) regimes or random lasing with non-coherent feedback are analysed.

Many years ago V. Letokhov [1] has suggested the laser scheme with multiple scattering at stochastic resonator. At this scheme the role of reflectors and scatterers have to play the large number of disordered grains immersed into some "cloud" of active media. During recent years the interest and studies of this scheme were renewed, and multiple scattering as feedback by energy for laser action has been studied experimentally in the visible part of spectra, in particular, for a dye systems with strongly scattering medium immersed (colloidal suspension) [2] and powder of laser crystals [3]. Recently this specific laser system was analyzed and discussed in more detail for the visible part of spectra for grinding crystals or micro spheres in dye solution [3, 4] (see also review [5]). Stochastic interelectrode cluster ensembles of vacuum discharge [6] look as potentially attractive ones to realize the random laser scheme namely at hard x-ray spectral intervals [7]. In fact, the mixture of "cold" clusters, nanoparticles and micrograins (reflectors and scatterers) and expanding number of clusters or microparticles exploded by current (hot microplasmas) as active media have to represent, in general, an ensemble of specific random media with potential x-rays amplifying properties. These properties will depend on the relation between characteristic amplifying and absorbing lengths l_{amp}/l_{abs} for a particular ensemble [1, 4].



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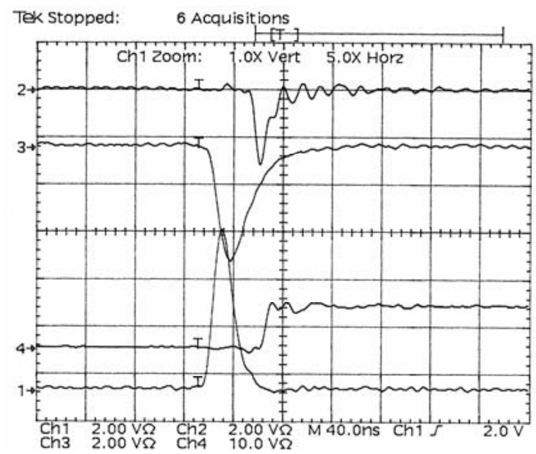

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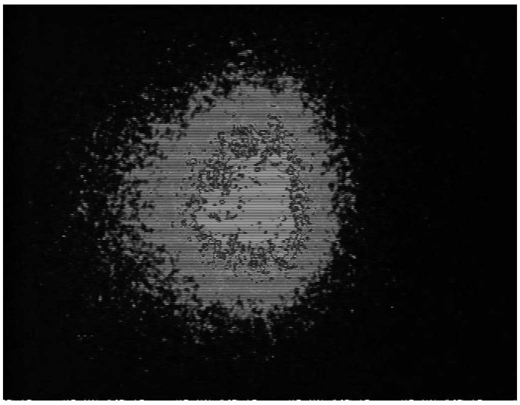
Fig. 1. CCD image of basic dilute inerelectrode ensemble (*a*); typical oscillogramms of x-rays intensities for basic ensemble (see text) (*b*)

At the present paper, we would like to pay attention for unusual ability of dense heterogeneous cluster media to provide the diffusions even for rather hard x-rays photons. It looks as one of the manifestation of principal feature of ensemble of nanoclusters: at decreasing of cluster sizes namely surface properties do prevail. Our experimental studies have recognized the opportunity of partial "trapping" of hard x-rays photons at increasing of clusters density in particular ensembles [6]. This feature is illustrated by comparison of data in Figs. 1 and 2. Usually, for dilute interelectrode ensembles (Fig. 1, *a*) the signal of photomultiplier (ch. 2, energy of photons > 60 keV [6]) is delayed (electronically, i.e., artificially) for about ~ 35 ns from instant PIN diodes x-rays signal 3–10 keV (channels 1, 3 it Fig. 1). Next, Fig. 2, *a* shows the ensemble of higher cluster density, where we may observe the beginning of *x-rays diffusion in cluster ensemble*. In fact, maxima of signals from ch. 2 and PIN diodes (chs. 1, 3) are coinciding approximately at oscillograms registered. But the maximum of very hard x-rays (channel 2) have to be "shifted" to the left on ~ 35 ns to compare with lower energy x-rays yield (chs. 1, 3) in real time. Diffusion-like delay with release of x-rays from ensemble registered by channels 1 and 3 is about ~ 40 ns (Fig. 2, *b*).



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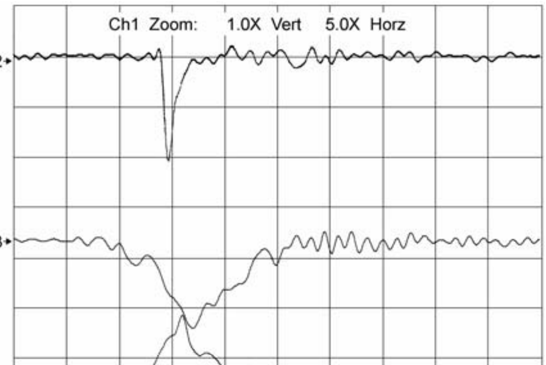

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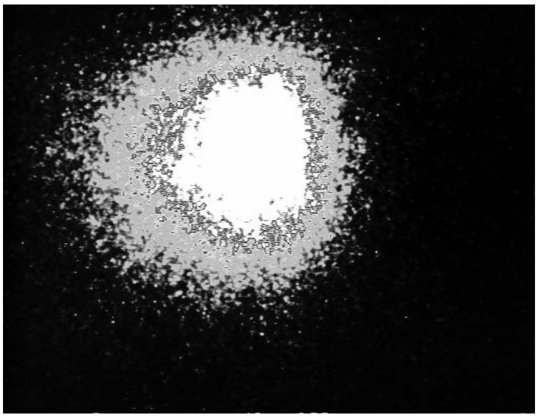
Fig. 2. CCD image of dense cluster ensemble with partial diffusion of hard x-rays (*a*); oscillogramms of x-rays intensities related. In real time the release of x-rays Registered by chs. 1, 3 is delayed in comparison with harder photons (ch. 2) (see text) (*b*)

The CCD images of diffused type at more higher cluster densities of ensemble sometime are not accompanied by the set of oscillogramms in principle (an example is presented on Fig. 3, *a*), since the intensity at ch. 1 turned out lower than needed very small triggering value ($U_{trig} = 100$ mV at channel 1). Another example of instantly self-organised ensemble with extremely low x-rays yield is shown at fig.3b. Here is the bright CCD image, with elements of self-organization in comparison with neighbour shots CCD images. Very low x-ray intensity at ch. 3 (which was not registered at similar level for shot at fig.3a) illustrates obviously hard x-rays "trapping" by nanoparticle ensemble on Fig. 3, *b* (fortunately, there is $U > U_{trig}$, ch. 1, and oscillograms have been registered for this shot).



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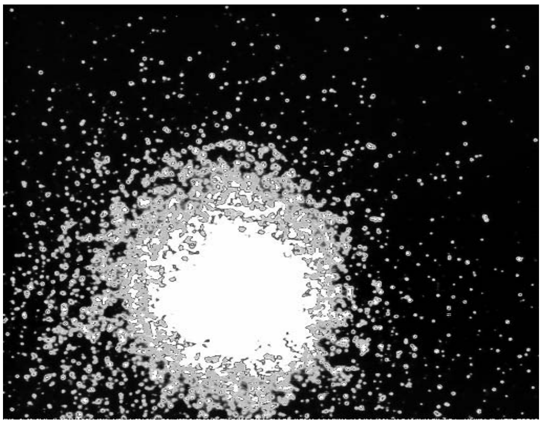

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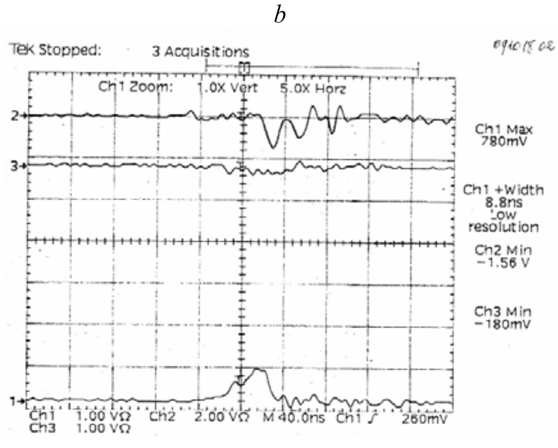


Fig. 3. CCD image of ensemble with very low x-rays yield (next shot after one on Fig. 2, *a*; $U_{chan1} < U_{trig}$) (*a*); CCD image of self-organized ensemble (*b*); almost trapped or suppressed x-rays from self-organized ensemble (Fig. 3, *b*) (*b*)

Thus, the ensembles with high level of symmetry may trap partially x-rays (~ 3–10 keV) and give almost no x-rays yield intensity (channels 1, 3), meanwhile this intensity from skin-layer of "ball" is enough to register the image by sensitive CCD camera. In a result, experiment shows that the character and level of multiple scattering of x-rays at nanocluster ensemble (passive media) might be essential under certain conditions and allow diffusion even for some hard x-rays. Concerning the active media, probably it could be identified with some of hot microplasmas of extreme parameters, created by percolation of current of high density through ensemble of clusters of heterogeneous sizes.

Let us make some estimates for possible effects of random lasing in interelectrode cluster media. To describe or analyze these mixtures, we introduce formal parameters α, β (characterizing the mean inter-grain distances to their mean diameters) and η (relation between numbers of cold and hot grains): $\alpha = N_c^{-1/3}/2a_c$, $\beta = N_h^{-1/3}/2a_h$, $\eta = N_c/N_h$, where N_c, N_h are average values of their radii, respectively. We illustrate on Fig. 4 some of the qualitatively different configurations and regimes of x-ray ensembles in terms of parameters α, β, η partially identified in our experiments. There are shown schematically, in particular, the "cold" anode flare dusty plasma before the end of breakdown (Fig. 4, *a*), initial overheating and expansion for the small fraction of grains during the main current rising, when arc phase has started (Fig. 4, *b*), and the overlapping of microplasmas that transformed into rather uniform and dilute cooling plasma with the rest of unperturbed and cold grains immersed (Fig. 4, *c*).

As an example of particular interest, we will consider the possibility of experimental realization of a laser scheme [1] when incoherent scattering of photons provides feedback by energy needed for random laser action. Available theory developed earlier [1] is a good reference basis for understanding the problem. Letokhov have considered the case when the mean free path of photons due to scattering $l_{sc} = 1/N_0Q_S$, ensemble radius R and the wavelength λ are related as $\lambda << l_{sc} << R$, and $N_0^{-1/3} >> \lambda$ (Q_S is scattering cross section, N_0 is volume density of scattering particles). Being trapped in disordered system, light or x-rays make a long random walk before it may leave the medium from near surface area.

The solution of the system of equations which describes diffusion of photons [4] shows that laser generation threshold may be achieved when volume gain become larger than surface losses at some ensemble volume which is above critical size, or at $R > R_{cr}$ in the case of sphere (looking forward, see Fig. 5 below). The critical radius is equal to $R_{cr} \approx \pi\,(l_{sc}/3\gamma_m)^{1/2}$, where γ_m is mean gain coefficient. In our case $\gamma_m = \gamma/\beta = \gamma 2a_hN_h^{1/3}$, $\gamma = Q_rN$. Here Q_r is the cross section for induced radiation transition; N is the density of inverted population that is difference of populations in higher and lower state of resonance transition. The scattering mean free length and gain are the key features for possibility of laser action.

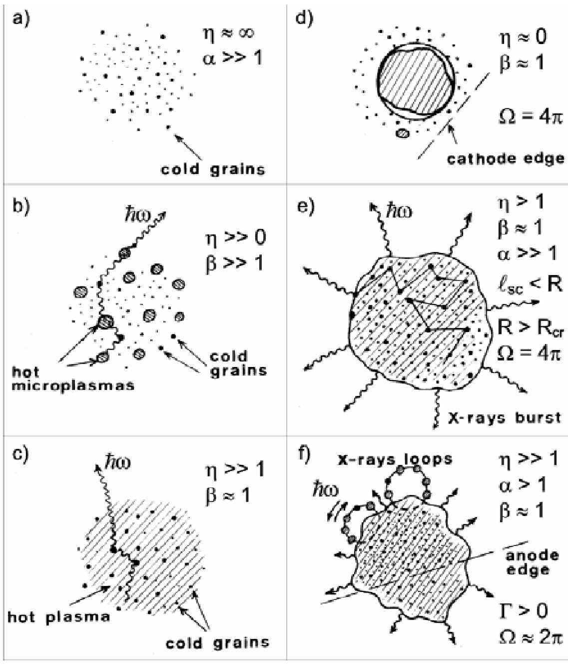
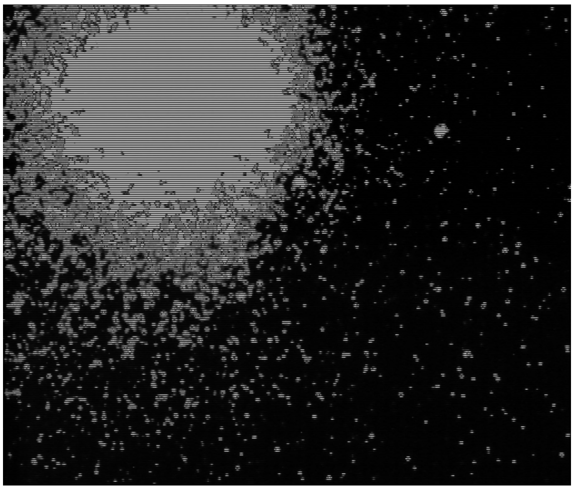


Fig. 4. Schematic of different types of configurations of ensembles of dusty interelectrodes media, registered and partially identified in experiments with hollow cathode discharge [6] (see text)

If one consider the case when hot non-equilibrium plasma merged in central sphere (radius of which is R) is surrounded by spherical layer of cold grain media, ΔR in thick, with scattering length l_{sc}, then reflection coefficient of outer layer will be $\Delta R/l_{sc}$. Then, laser threshold condition will be $(\Delta R/l_{sc})\exp(\gamma R/\beta) > 1$, that determines the critical radius. Note that the role of nanoclusters surface in small angle scattering processes (at near grazing angles) may essentially reduce the x-rays random laser threshold. To illustrate the prevailing of surface properties at decreasing of nanoparticles radii and increasing of their number we may rewrite $l_{sc} = 1/N_0Q_S$ as $l_{sc} = V_{1clus}/V_{clusters}\ S_{1clus.}$ (V_{1clus} is the mean volume of single cluster, $V_{clusters}$ is the relative volume of nanocluster ensemble). Then at cluster radius $r_{clus} \to 0$ we have $S_{1clus}/V_{1clus} \to \infty$ and $l_{sc} \to 0$ that provides x-rays diffusion inside of interelectrode nanoparticle ensemble (under $V_{clusters} \approx$ const from shot to shot). Since metallic nanoclusters are nanocrystalls, the specific role of exact Bragg reflection and scattering in volume as well as by cold shells (Figs. 2, *a*, 3, *a*, 3, *b*) as effective "ring resonators" [7] need separate analysis.

Example of bright ensemble with strong x-rays anisotropic burst is shown at Fig. 5, *a* for the shot with Fe anode. Some specific spikes which are usually typical ones for lasing can be observed at x-rays inten-



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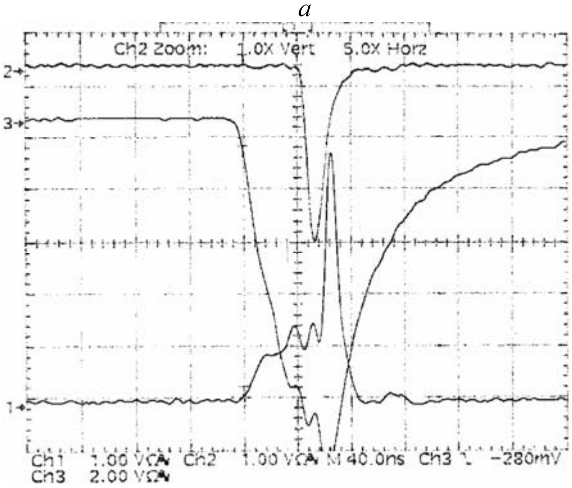

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Fig. 5. CCD image of ensemble with strong anisotropic hard x-ray burst (*a*); oscillogramms of x-rays intensities from ensemble (Fig. 5, *a*) with possible hard x-rays random lasing (sensitivity of ch. 1 is 1 V and for ch. 3 is 2 V) (*b*)

sities from chs. 1, 3 (Fig. 5, *b*). In fact, the conditions of this shot are close to the situation when volume gain becomes larger than surface and volume losses, i.e. represents *random hard x-rays lasing*. (Hhowever, quantitative x-rays spectroscopy measurements are needed at further experimental study). Looks that this is x-rays analogy of random lasing at colloidal suspension in visible light observed and discussed earlier [2]. X-rays ensemble at Fig. 5 corresponds to scheme presented at Fig. 4, *e* approximately. Note, as in the case of optical transport in scattering media [8], the transport velocity of photons with energy of few keV due to their diffusion inside of ensemble may be about 2–3 order of magnitude less than in vacuum.

In summary, we may conclude that discharge conditions exist when plasma radiates x-rays from diffuse spot with very high intensity and strong asymmetry in directions. One can observe oscillations of intensity in some cases. As it was shown by Letokhov [1], all such features are typical for random lasers with nonresonant feedback in scattering medium. Note that a short-wave length laser with recombination pumping of active medium formed from a cloud of identical clusters discussed at paper [11]. The maximum useful volume of the active medium was estimated as about 4.6%. It might correspond to general structure of nanocluster interelectrode ensembles at vacuum discharge also [12], but another sources of pumping like, for example, fast ions collisions with clusters as well as the role of Fe^{57} have to be analysed also.

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