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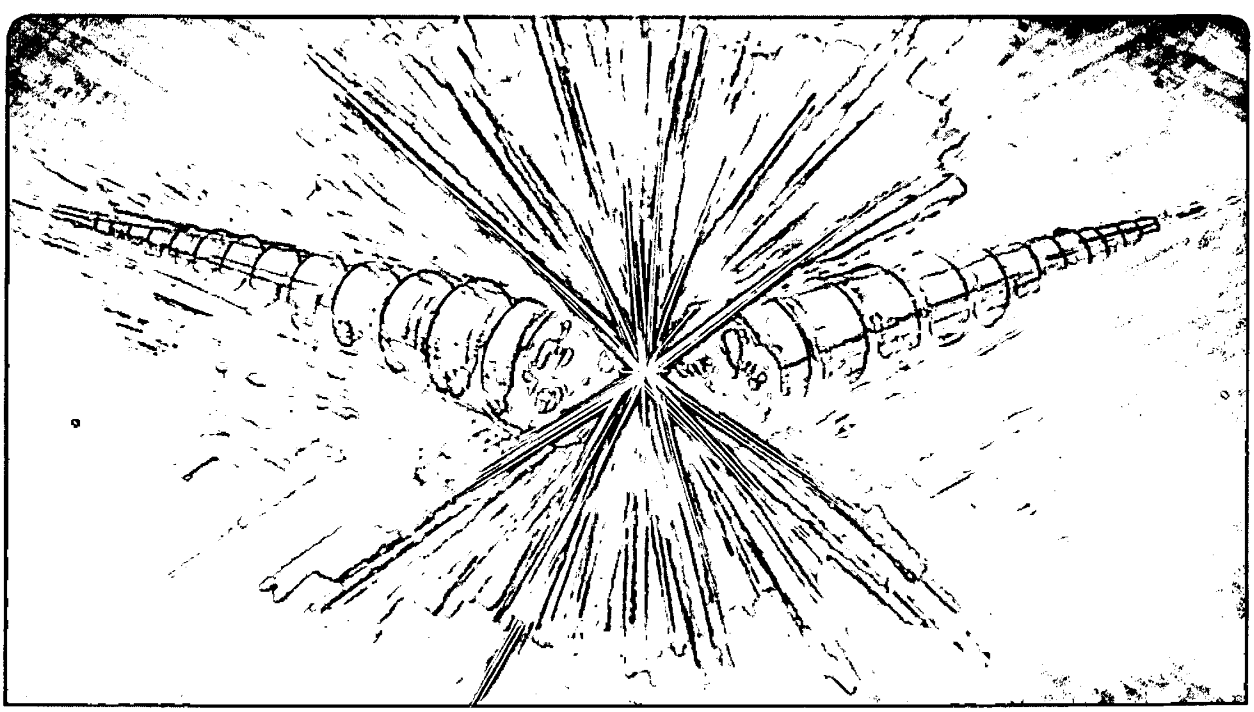

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HEAVY IONS ACCELERATION IN RF WELLS OF 2-FREQUENCY ELECTROMAGNETIC FIELD AND IN THE INVERTED FEL

A.I.Dzergach, V.S.Kabanov, M.G.Nikulin, S.V.Vinogradov

Summary

Last results of the study of heavy ions acceleration by electrons trapped in moving 2-frequency 3-D RF wells are described. A linearized theoretical model of ions acceleration in a polarized spheroidal plasmoid is proposed. The equilibrium state of this plasmoid is described by the modified microcanonical distribution of the Courant-Snyder invariant ("quasienergy" of electrons).

Some new results of computational simulation of the acceleration process are given. The method of computation takes into account the given cylindrical field $E_{011}(\varphi,r,z)$ and the self fields of electrons and ions. The results of the computation at relatively short time intervals confirm the idea and estimated parameters of acceleration.

The heavy ion accelerator using this principle may be constructed with the use of compact cm band iris-loaded and biperiodical waveguides with double-sided 2-frequency RF feeding. It can accelerate heavy ions with a charge number Z_i from small initial energies $\sim$ 50 keV /a.u. with the rate $\sim Z_i \cdot 10$ MeV/m.

Semirelativistic ions may be accelerated with similar rate also in the inverted FEL [1].

1. Introduction

Compact accelerators of heavy ions with high energies ~100 MeV/a.u. may have many applications (see, e.g., [2]). The corresponding accelerator elaborations are based on modifications of classical circular or linear acceleration schemes and lead to comparatively large machines.

During the discussion in June 1993 in the Moscow Radiotechnical Institute of charged particles acceleration in RF wells (see [3] and references therein) prof. A.M.Sessler had proposed to investigate the possibility of heavy ions acceleration by means of RF wells and of inverted FEL. First results of this investigation [1] which is conducted with the support of prof. A.M.Sessler are encouraging and described below in up-to-date version.

The supposed accelerator [1] consists of a series of sections. Each section is an iris-loaded waveguide or a similar structure, with a certain longitudinal variation of parameters (in case of iris-loaded waveguide – mainly the cells lengths) and with double-sided RF feeding at a pair of frequencies.

The frequency difference is relatively small in the 1-st sections , $\delta \approx (\omega_1-\omega_2)/(\omega_1+\omega_2) \approx 1\text{–}3\%$, and grows in next sections, which are more wide-band.

Two counterrunning slow waves $E_{01} \equiv TM_{01}$, which have corresponding wavenumbers, form 3-dimensional moving RF ponderomotive potential wells for electrons.

The velocity of the wells $v_z = (\omega_1-\omega_2)/(k_1+k_2)$ may be increased 2-2.5 times as much in each section (in the weakly-relativistic part of the accelerator) by means of the longitudinal variation of

$k_{1,2}(z)$. In other words, the relative velocity of the wells is connected with the phase velocities $\beta_{1,2}$ of the slow waves by the formula

$$v_z/c = \beta_z = \frac{\omega_1 - \omega_2}{\omega_1/\beta_1 + \omega_2/\beta_2} = \delta \cdot \frac{\omega_1 + \omega_2}{\omega_1/\beta_1 + \omega_2/\beta_2}. \quad (1)$$

It corresponds to the ions energy growth by 4–6 times in each section. So the acceleration of ions say from ~50 keV/a.u. to 100MeV/a.u. is possible in several sections. The last sections where the velocities of ions exceed $\sim$ 0.1c, may be of the IFEL type (one frequency and a magnetostatic wave).

For instance, the 1-st section is fed at $\lambda_{1,2}\approx 3$ cm (δ=0.025) and accelerates from β_1=0.01 (50 keV protons) to β_2=0.025 (300 keV protons); the 2-nd section (more wideband) is fed at $\lambda_{3,4}$=1cm (δ=0.1) and accelerates from β_2=0.025 to β_3=0.06 (1.7 MeV protons).

The 3-d section accelerates to β_4=0.15 (10 MeV protons), the 4-th section – to β_5=0.37 (72 MeV protons).

The acceleration rate (accelerating force) for ions with charge number Z_i is estimated [1] as $E \sim Z_i \cdot 100$ keV/λ, λ being the mean wavelength in a section.

In case of using the klystrons and compact accelerating structures of 1-cm band [4] the acceleration rate will reach ~$Z_i \cdot$ 10 MeV/m , which is several times higher than typical values for classical schemes.

For instance, the accelerator for ions with a charge number 5 and the final energy 100 MeV/a.u. will have the length $\sim$2 m.

The principle of the supposed 2-frequency accelerator [3] consists in localization and acceleration of positive ions trapped by electrons in RF wells. In contrast to the plasma beat-wave acceleration (Tajima. and Dawson, 1979), we use small (characteristic dimension ~ several Debye lengths) plasmoids, isolated by the RF wells, instead of a long plasma fiber; our plasmoids density is relatively high, $n \approx 0.3\, n_c$ instead of $n \approx 0.01\, n_c$, $n_c = m\omega^2\varepsilon_0/e^2$ being the critical density; the plasmoids repetition frequency is also high, $(\omega_1+\omega_2)/2$, instead of $\omega_1-\omega_2$ in the PBWA scheme; we use forced oscillations instead of resonant ones which gives us freedom from some restrictions of the PBWA .

The numerical simulation was made with the use of the PC AT-386 by a version [1] of the method of particles in cells for the case of the simplified model: one plasmoid (in some cases – purely electronic) in the RF well of a cylindrical resonator with a 1-frequency standing wave $E_{011}(\varphi,r,z)$. This wave corresponds to a pair of counterpropagating swift waves E_{om} with equal frequencies in a tube (steady RF wells) or different frequencies (running wells).

In order to lower the RF powers in this accelerator we use slow waves in an iris-loaded or similar waveguide. The corresponding change from usual Bessel functions $J_{0,1}(k_r r)$ to modified ones, $I_{0,1}(k_r r)$, will not lead to substantial changes in the particles motion, because the distinctions of these functions do not exceed ~5% in the plasmoid area. The influence of the other space harmonics was ignored because they are asynchronous with the plasmoids.

More detailed computations must be connected with the boundary conditions for plasmoids moving through the cells of say the iris-loaded waveguide,the interaction of plasmoids and the influence of idle space harmonics. We suppose that the distinctions between the simplified model (cylindrical resonator) and the more realistic model (iris-loaded waveguide) will be small, but this supposition deserves a proof at a more powerful computer.

The results of our computations for rather arbitrarily chosen initial conditions show some loss of particles in the acceleration process. We suppose that these losses are not fatal but they are connected with incomplete adoption of the initial conditions with the RF well (see below).

The pulse current limit of this accelerator was estimated [1] as $I_a \sim 0.1$ A for the case of $Z_i = 1$. This current may be increased in case of using thoroidal RF wells in a tubular waveguide with swift waves or in case of using a wide rectangular loaded waveguide with a ribbon beam divided by "rods" in RF wells.

2. About the analytical linear model of plasmoid acceleration in the RF well of a 2-frequency field

An electron (or positron) oscillations in the RF well of the cylindrical field E_{011} ($E_z = \hat{E} J_0(k_r r) \sin k_z z \sin \omega t$ etc.) are described in a general case by a pair of nonlinear differential equations, because the field variation in space is nonlinear (Bessel functions $J_{0,1}(k_r r)$ or $I_{0,1}(k_r r)$, sinusoidal functions of $k_z z$, where $k_z^2 = (\omega/c)^2 \pm k_r^2$, $\pm$ correspond to slow/swift waves. Besides of it the nonlinearities are connected with the term $\vec{v} \times \vec{B}$ and with the relativistic mass.

But in case of small initial deviations, $|k_r r| \ll 1$, $|k_z z| \ll 1$, and of corresponding small initial velocities, the motion of electrons (without of acceleration) in a charged may spheroiud be described by the Mathieu equations

$$z''(x) + (a_z + 2q_z \sin 2x) z = 0, \qquad r''(x) + (a_r + 2q_r \sin 2x) r = 0, \qquad (2)$$

where $q_z = 2e\hat{E}\lambda \cos b / 2\pi mc^2 = -2q_r$, $a_z = -4e\rho\lambda^2 M_z / 4\pi^2 \varepsilon_o mc^2$, $a_r = a_z M_r / M_z$.

The formfactors $M_{r,z}$ of the charged spheroidal plasmoid correspond to its field expressions

$$\varepsilon_o E_z = M_z \rho z, \quad \varepsilon_o E_r = M_r \rho r, \quad 2M_r + M_z = 1 . \qquad (3)$$

The radiation (bremsstrahlung) of electrons and their magnetic interaction are neglected.

The ratio 2 of the oscillating coefficients $q_{r,z}$ in (1) corresponds to the ratio of radial and axial gradients of the cylindrical field at its axis. It leads here to the anisotropy of the AG focusing. In case of thoroidal wells these coefficients are almost equal and the AG focusing is almost isotropical.

The linear model of a spheroidal plasmoid in the RF well which is proposed here is similar to the known self-consistent model of a beam in a quadrupole channel [5]. The distinctions are connected with the Mathieu equations instead of Hill equations, with the *rz*-anisotropy and with the oscillating quadrupole surface charges at the motionless boundaries of the electron-ion plasmoid instead of quadrupole oscillating boundaries in case of purely electron plasmoid or purely ion (electron) beam.

Stable solutions of the Mathieu (and Hill) equations have the form of products of HF and LF functions. The HF function oscillates with the field frequency ω about some positive value. The low-frequency functions, $exp(\pm i\Omega_{r,z} t)$, correspond to the Floquet phase advances per field period, $\Omega_{r,z} = \omega\mu_{r,z}/2\pi$.

If the charge density $\rho \to 0$, then the frequency ratio Ω_z/Ω_r is equal to the ratio of the HF z- and r-gradients (=2 in case of the spheroid) and these frequencies $\Omega_{r,z}$ are several times lower than the ω in our cases. The semi-axes ratio r_s/z_s may have any value.

If the density ρ is not small, then the frequencies $\Omega_{r,z}$ depend not only on the HF gradients, that is on $q_{r,z}$, but also on the $a_{r,z}$ values, that is on the ρ. The upper limit for $|a_{r,z}|$ is defined by the boundary of the 1-st Mathieu stability zone in the a,q plane (see, e.g., [6]):

$$a = -q^2/2 \ . \tag{4}$$

This condition gives in our spheroid case

$$a_z = -q_z^2/2 \ , \qquad\qquad a_r = -q_z^2/8 \ . \tag{5}$$

This 4-fold ratio of constant coefficients $a_{z,r}$ and $M_{z,r}$ (M_z=4/6, M_r=1/6) leads to the corresponding ratio of the spheroid semi-axes,

$$z_s/r_s \approx 1/3 \ . \tag{6}$$

In this flattened along the z-axis (lens-like) spheroid the increasing of density leads to the simultaneous instabilities in both directions, r and z. If the axes ratio is not equal to 1/3, then the stability is not isotropic. The r- and z-oscillations are independent in the linear approximation, so we may have, e.g. r-stability and z-instability in the same spheroid.

The distribution function of plasmoid electrons, $f(\vec{r},\vec{v})$ in the 4-dimensional phase space (the azimuthal distribution is uniform, and the azimuthal velocities $\dot{\phi}$=0) which corresponds to stable oscillations and to a self-consistent solution of the Vlasov equation is similar to the Kapchinsky-Vladimirsky equilibrium [5]:

$$f(\vec{r},\vec{v}) = \delta\ (I_r + I_z)\ ,$$
$$I_r = (r/\sigma_r)^2 + \sigma_r^4 (r/\sigma_r)', \qquad I_z = (z/\sigma_z)^4 + \sigma_z^4 (z/\sigma_z)'\ , \tag{7}$$

where $r=r(x)$, $z=z(x)$; $\sigma_{r,z}(x)$ are the Floquet amplitudes, corresponding to the equations (2) ; the primes (′) denote the 1-st derivatives d/dx .

The Courant-Snyder invariants ("quasienergies") correspond to the smoothed, or normalized oscillations. The true energy oscillates between the field and particles.

So, if all electrons (or positrons) in the flattened spheroid with oscillating boundaries have equal "quasienergies" then the integration of the δ-function by the velocities leads to uniform density in our *rz*-plane and to mathematical stability (equilibrium state). All basic properties of our electron spheroid are similar to the properties of the beam in [5]; in particular, there is no "boundary particle" and the motion is not Brillouien-like.

Similarly to the quadrupole channel here may be matched or not matched initial conditions relatively to the focusing system.

If the initial conditions are matched, then the envelopes (spheroid boundaries) oscillate periodically with the field frequency ω.

In the presence of ions the surface charges play the role of the oscillating boundaries.

If the initial conditions are not matched, then the $\Omega_{r,z}$-oscillations will be superposed on the ω-oscillations. In order to avoid this mismatching one may use the iterational procedure [5] of finding the matched initial conditions for the spheroid.

Introducing of positive the ion frame in this electronic spheroid leads to lowering of the repulsing coefficients $|a_{r,z}|$ proportionally to $(n_e - n_i Z_i)$. Some excess of electrons may be useful for the phase stability of the accelerated ions. The boundary of the ion spheroid must correspond to the mean boundary of the purely electron spheroid. Then the r–z-oscillations of surface quadrupole charge density will substitute the envelope oscillations and the internal field of the spheroid will be linear.

Which will be the changes in case of acceleration?

In the right side of the z-equation (2) a term proportional to the acceleration will appear, evidently, if we describe the motion in the accompanying frames.

The wavenumbers $k_{r,z}$ will be slowly varying functions of z. For instance, if the acceleration is uniform, $v = v_o + at$, then

$$1/k_z(z) = 1/k_{zo} + 2\gamma/\omega \; (v_o^2 + 2az)^{1/2} \tag{8}$$

where the Lorenz-factor $\gamma \approx 1$ in the initial part of the accelerator.

Variation of k_r corresponds to the condition $k_r^2(z) + k_z^2(z) - (\omega/c)^2$. These variations lead to growth of the spheroid volume . So we have the "bottleneck" at the injection, as usually. (In case of swift waves we have the opposite situation).

The inhomogenuous longitudinal Mathieu equation in the acceleration regime is similar to the equation of off-momentum particles closed in a strong focusing synchrotron. The radial equation (2) remains unchanged.

The acceleration is connected with the emergence of dipole surface charge layers on the leading (–) and rear (+) edges of the plasmoid. These dipole layers are the sources of the polarization field which accelerates the ions and of coherent re–radiation from the higher frequency to the lower one.

Here again two cases are possible – matched or mismatched initial longitudinal conditions of the ion frame relative to the electron spheroid.

In the matched case the "ion centre" has some constant lag behind the mean position of the "electron centre". The electron centre oscillates longitudinally around its mean position (lagging from the RF well center) with the field frequency ω.

In the mismatched case additional Ω_z oscillations arize. Their amplitude is defined by the dismatch. The acceleration does not have any influence on the stability in the linear model, because the linear field zone and the spheroid dimensions may be infinite.

This linear model may be useful for the choice of initial conditions and for the comparison with results of numerical computation of many interacting particles motion in the linear regime (small central zone). And may be it will be useful for some special version of computation algorithm.

To our regret we have not any method of finding the maximum tolerable plasmoid dimensions besides of gradually enlarging the initial deviations at various field prarmeters. May be some modification of the field structure will be useful, e.g., a slow variation of the HF field or superposition of longitudinal magnetic field.

3. On the influence of the HF-wells acceleration and partial charge neutralization on the plasmoids structure and stability. Numerical modeling results

The first question it is necessary to answer using the numerical modeling is whether the plasmoids remain stable if the HF-well moves with any acceleration and how this acceleration influences on the plasmoid's characteristics.

For the studying of the corresponded effects in some variants all particles (electrons) were considered to be under the action of any force $\vec{F} = m\vec{a}$ (additional to the electrical forces) directed counter z axis. This means that we watch the particles' motion in the non-inertial coordinate system, where the HF-well doesn't move, and neglect the variations of the HF-well characteristics (such as k_z and k_r variations) during the acceleration. The numerical model we used was described in detail in the interim report.

The influence of the acceleration on the plasmoid structure may be seen from the comparison of Figs. 1 and 2. On Fig.1 the configuration portraits of an accelerating plasmoid in consequent time moments are presented, and on Fig.2 the corresponded pictures for zero acceleration are shown (all other parameters are the same).

The system characteristics for both variants were as follows: the ratio z_{max}/r_{max} = 0.5, the amplitude coefficient $q = e\hat{E}\lambda/2\pi mc^2 = e\hat{E}/mc\omega = 0.45$. The acceleration in the variant 1 was $a = 1.7 \cdot 10^{-2} e\hat{E}/m$ (or 0.05 c^2/r_{max}).

If there is no acceleration the equilibrium plasmoid in the HF-well with the parameters described above represents itself an oblate ellipsoid of revolution with the longitudinal to transverse dimensions ratio about 1/4 (Fig.2). The electrostatic field of this plasmoid (after surplus electrons leaving the system) reaches approximately $E_p \sim 0.25\,\hat{E}$ near the ellipsoid border on the axis.

Under the action of the acceleration the plasmoid's form becomes asymmetric, it displaces notably from the HF-well's center (Fig.1) and, according to modeling results, the number of electrons (and electrostatic field E_p respectively) in it diminishes approximately by a factor of two. Nevertheless the plasmoid remains stable and capable to trap and accelerate ions. It should be noted, that the considered acceleration is at least 100 times greater than the one maximum possible for ions to remain trapped $a_{max} = E_p/m_i\,q_i$ (we consider this case only to visualize the corresponded effects). This means that for real rates of ion acceleration the inertial forces' action on the electrons will not be significant and the plasmoids' form distortions may occur only due to ions' displacement inside them.

The second task for numerical modeling was to explore the influence of ions' presence on the plasmoid structure. The evolution of the plasmoid with electrons and protons is shown on fig. 3. The initial charge of the protons in this variant is 20% of the electrons charge, the ratio $z_{max}/r_{max} = 0.5$, the amplitude coefficient $q = 0.3$. The configuration portraits of electrons are shown on the left side of each picture, and portraits of ions – on the right side. For comparison with fig.3 the variant presented on fig. 4 combines both ions (protons) presence and acceleration $a = 4 \cdot 10^{-5}\ c^2/r_{max}$ (other parameters are the same).
It is seen, that in this case the electrons' leakage from the plasmoid is notable not only for several initial HF-oscillations, but for al time of acceleration (probably it is related with E_{010}

mode generation due to currents in z direction), and this in turn leads to the final ions loss from the plasmoid, but to this moment the velocity of accelerated ions can reach $0.4c$.

4. Conclusion

The main results of the work described here are:

1) the scheme of compact accelerator of heavy ions is proposed, based on a series of iris-loaded waveguides and similar more wide- band, e.g., biperiodical waveguides; each of them is feed from opposite ends with different frequencies, which gives moving RF wells; longitudinal variation of the sells of sections leads to the increase of the velocity in each section by 2-2.5 times;

2) simulation of many particles dynamics in the 3-dimensional RF well has confirmed the preliminary estimations of acceptable plasmoids density and of electromagnetic and plasmoid's fields, namely, the density may reach the value ~ $0.3n_c$, the e.m. field amplitude $\hat{E}$ ~ 1MeV/λ, the plasmoid's field ~ $0.3\hat{E}$;

3) the acceleration gradient is estimated as ~ $0.1\hat{E}Z_i$, which may give in case of using λ~1cm and the charge number $Z_i=5$ the possibility to accelerate heavy ions in RF wells up to ~100MeV/a.u. at a length ~2m; the accelerated current is ~0.1A;

4) the acceleration of heavy ions in the inverted FEL may be effective only at relatively large velocities, β >0.2; this 1-frequency scheme may be used as a final section of the accelerator, but some difficulties are possible in the transfer of plasmoids from the 2-frequency part of the accelerator, because the interval between the plasmoids in the 2-frequency part is several

times shorter than in the IFEL;

5) the numerical simulation must be prolonged with more realistic mathematical model, taking into account not only 2 slow space harmonics, but all of them corresponding to real boundary conditions in the loaded waveguide. It may be done with a powerful computer;

6) besides of the more realistic numerical simulation and corresponding theoretical studies it would be useful to project the experimental model of the 2-frequency accelerator of heavy ions;

7) some results of this work may serve as verification of the method of laser acceleration by means of HF wells.

8) the results of the work confirm the supposition of prof.A.M.Sessler (June 1993, Moscow) about the possibility of a compact accelerator of heavy ions based on the RF wells.

References

1. A.I.Dzergach, V.S.Kabanon, M.G.Nikulin and S.V Vinogradov. Heavy ions acceleration in two-frequency electromagnetic field. Interim report. Moscow, March 1994.
2. A.A.Vasiljev. Problems of heavy ion accelerators . In: Proc. of the 6-th All-Union Particle Accalerators Conference, Dubna, 11-13 October 1978. Vol. 1, p. 37-42 (in Russian).
3. A.I.Dzergach. Nuclear Instruments and Methods in Physics Research A344(1994)260-268.
4. D.P.Aalberts, A.M.Sessler, G.A.Westenscow et al in: Proc. of the 1990 Linear Accelerator Conference. September 10-14 1990, Albuquerque, New Mexico, p. 192-194.

5. I.M.Kapchinski. Particle dynamics in linear resonant accelerators. Atomizdat, Moscow, 1966 (in Russian).
6. M.Abramovitz, I.Stegun. Handbook on special functions. Moscow, 1979 (in Russian).

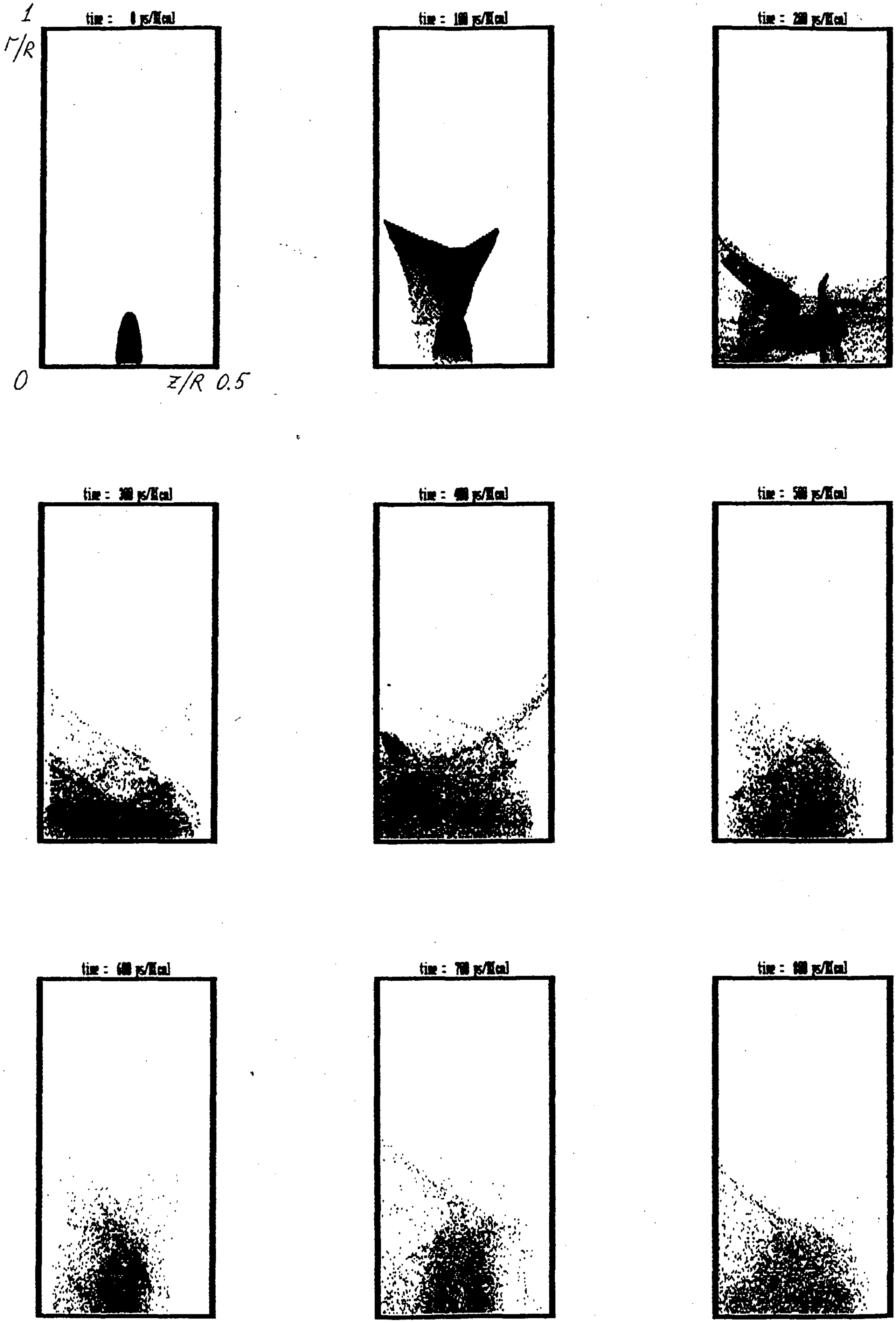
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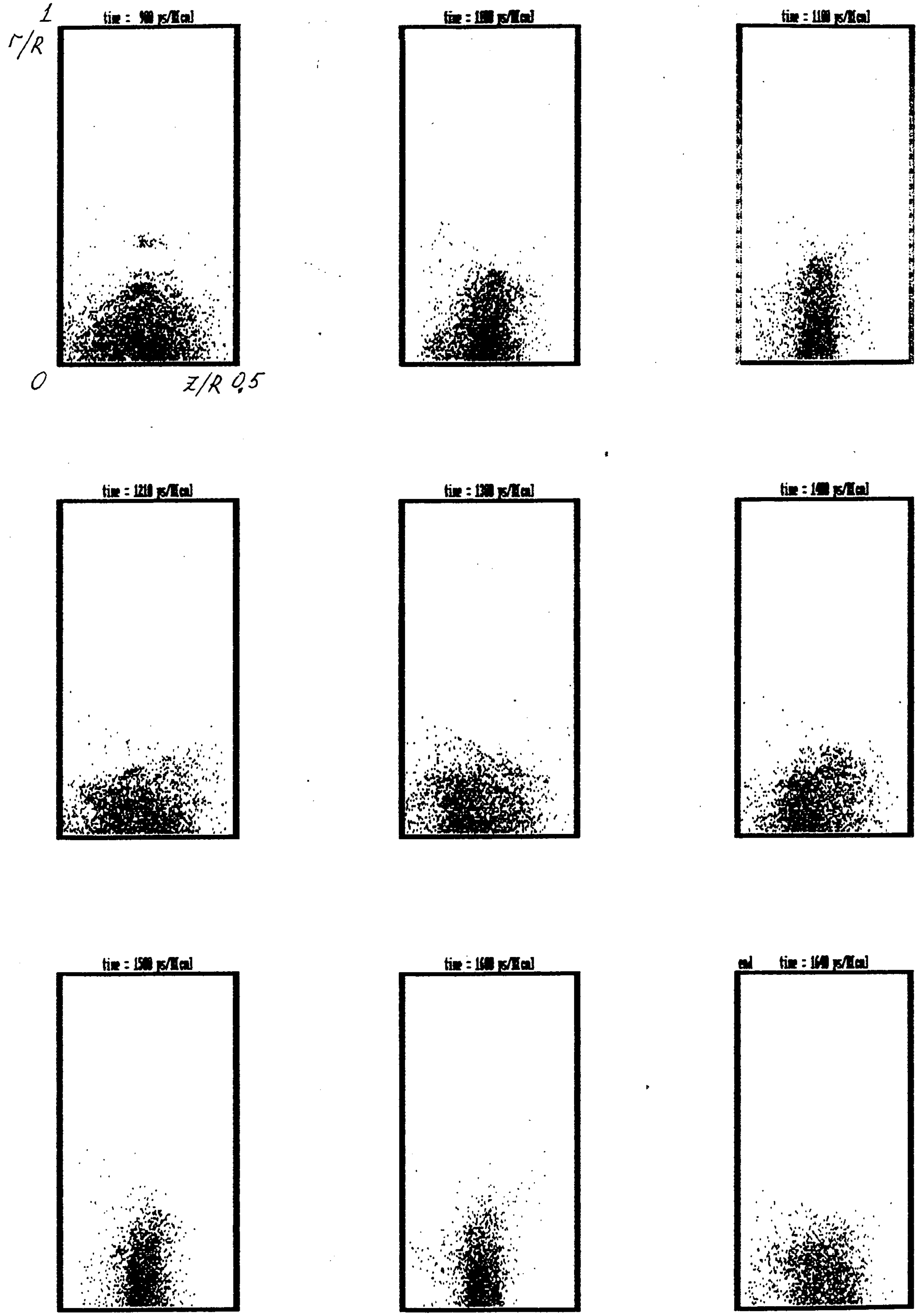
Fig. 1, a



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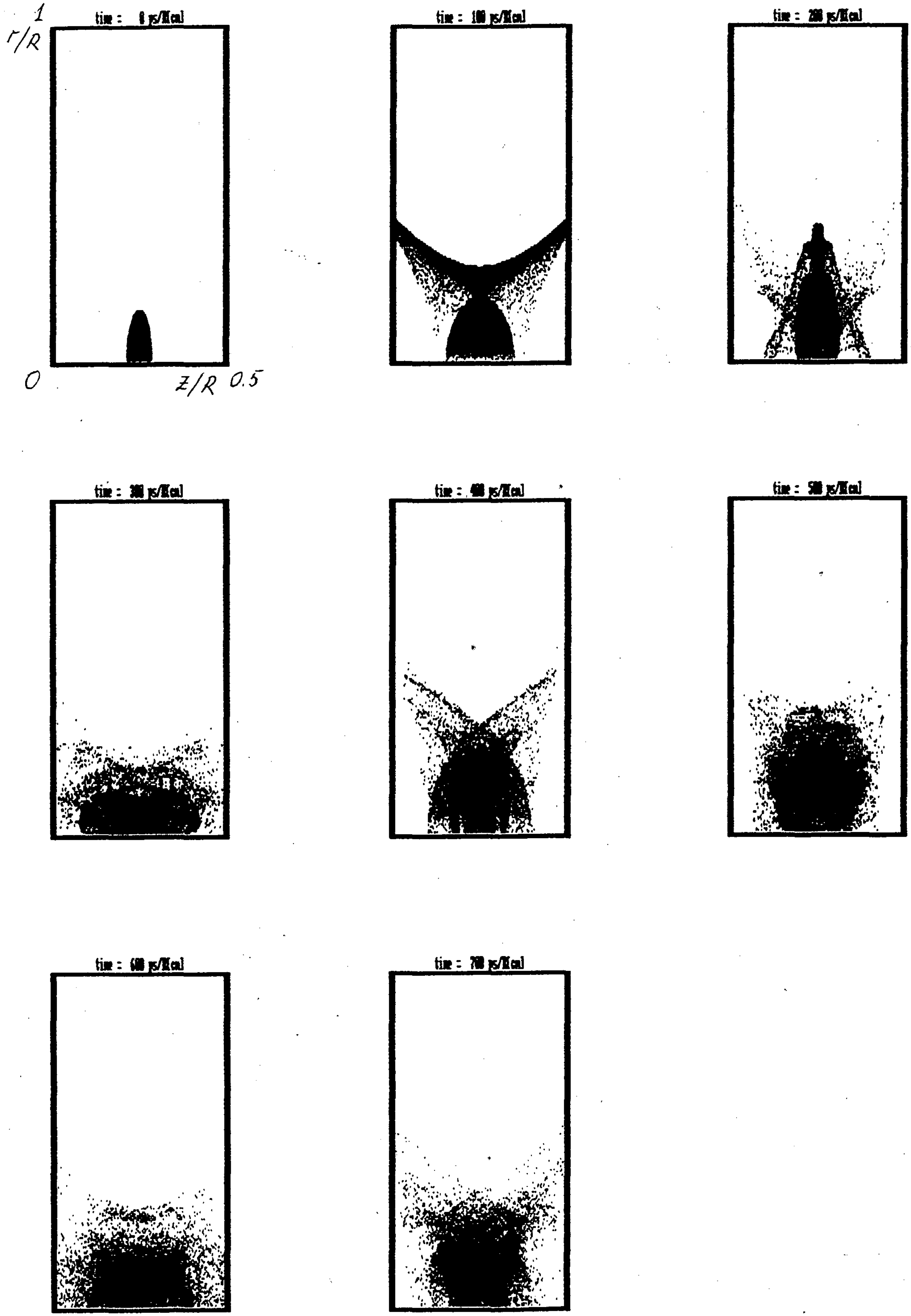

Fig. 2

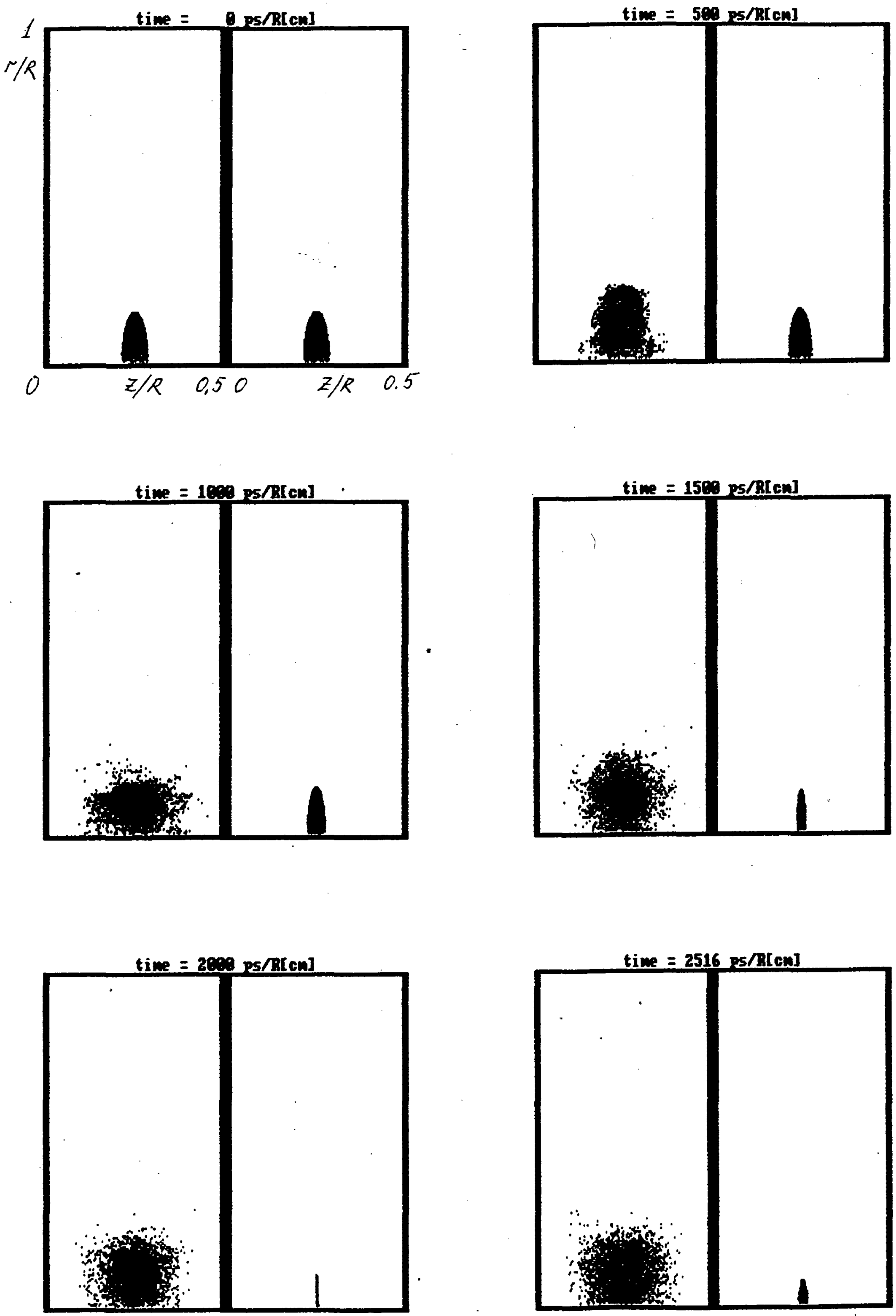
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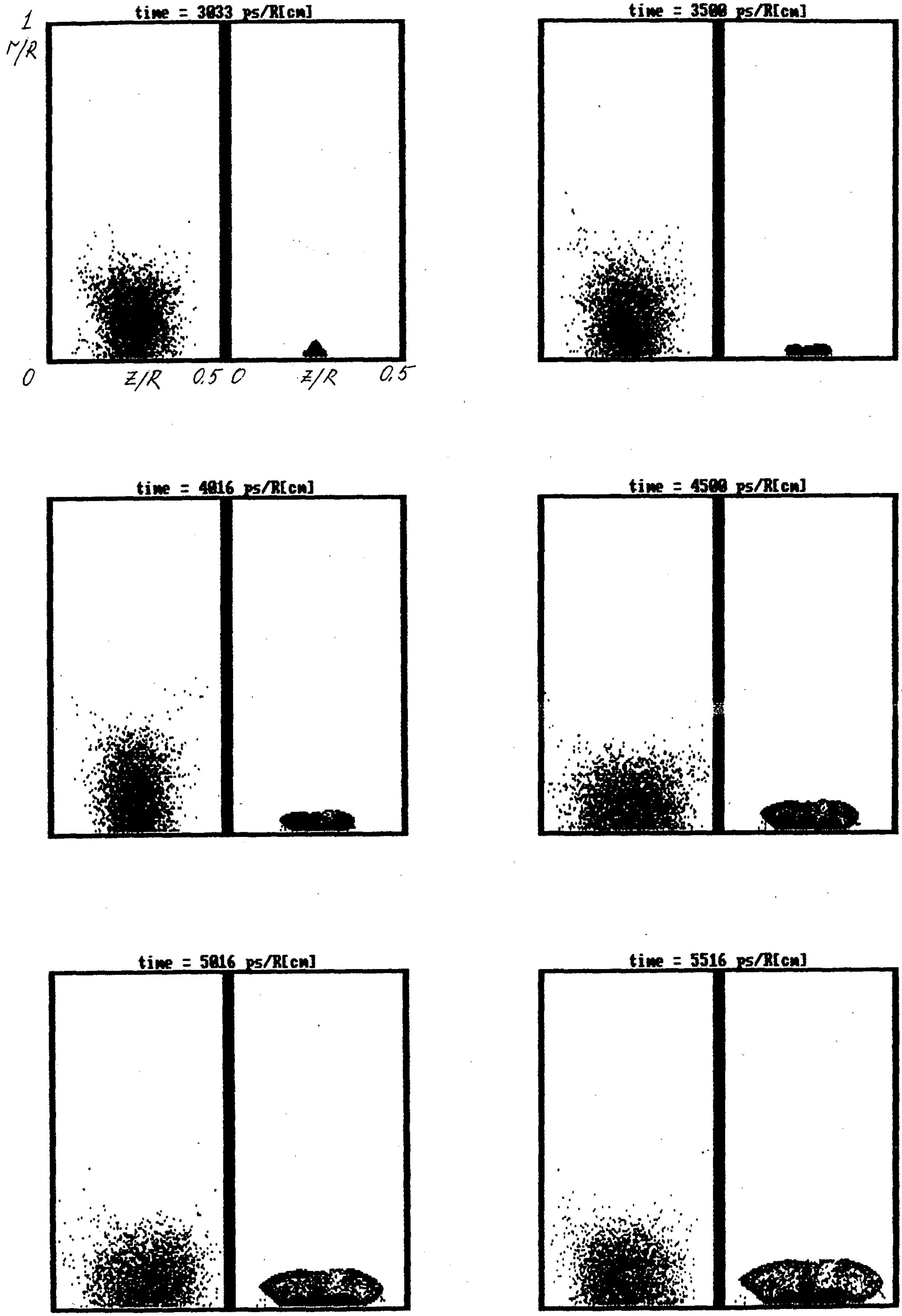
Fig. 3,a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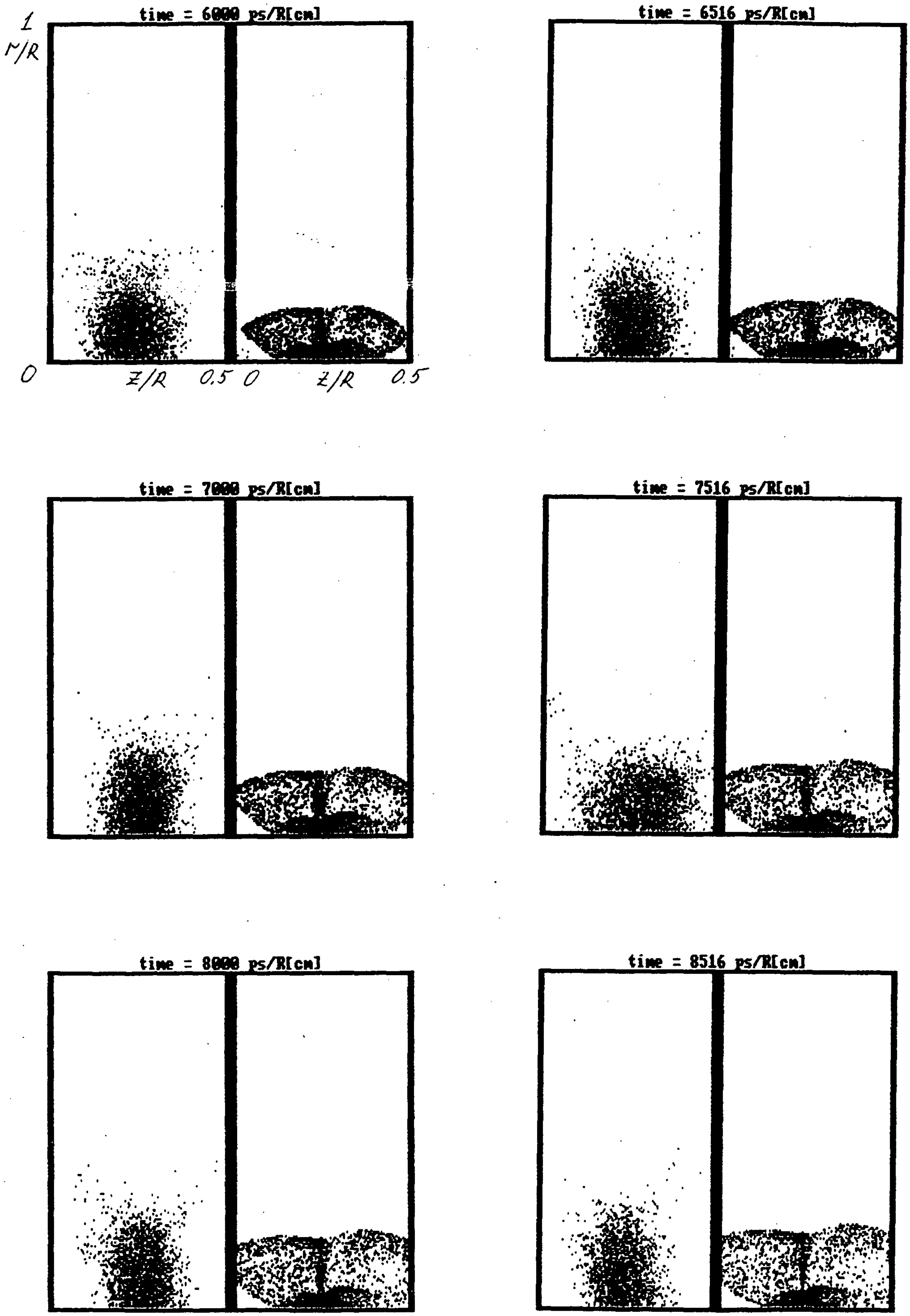
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Fig. 3,c

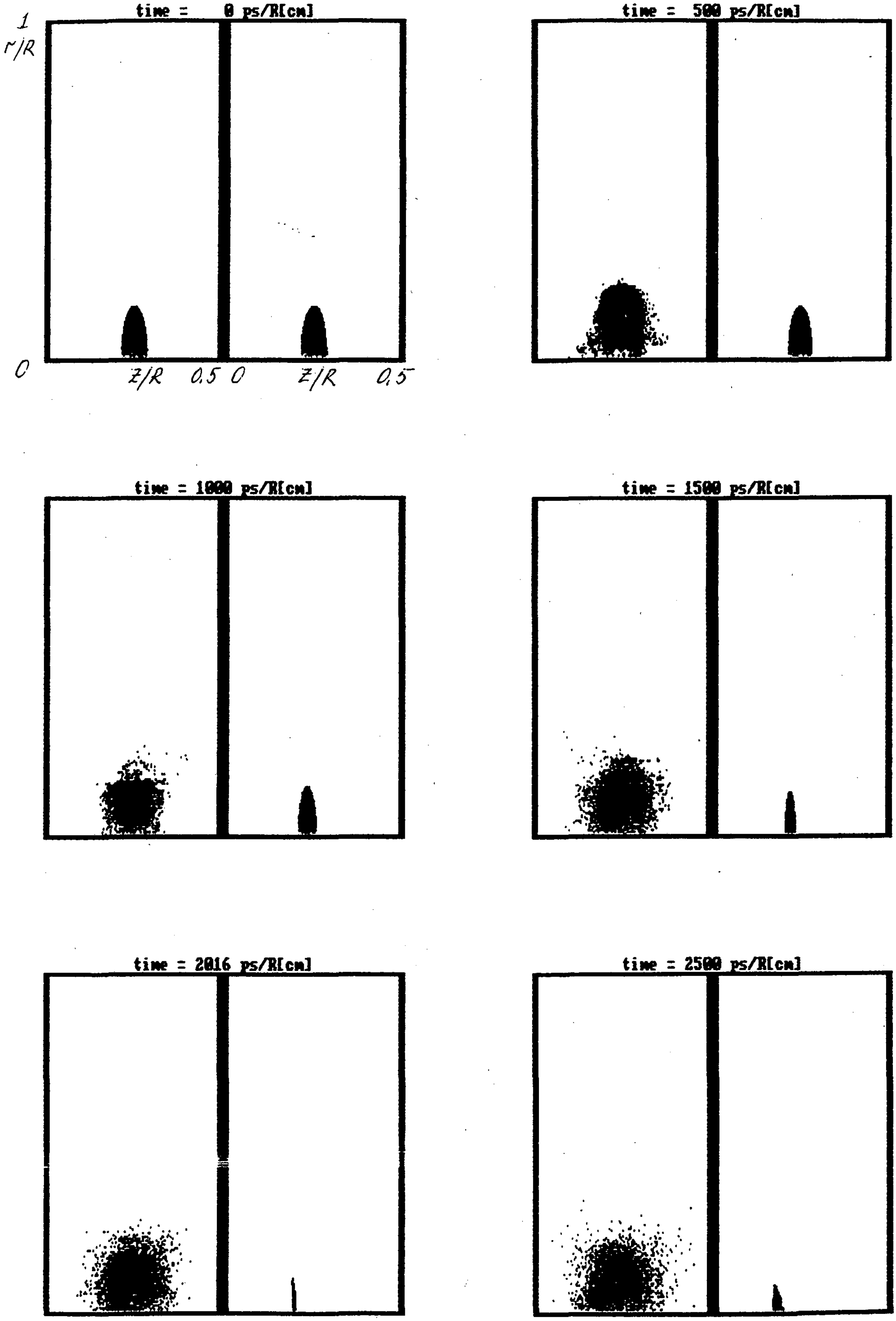
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Fig. 4,a

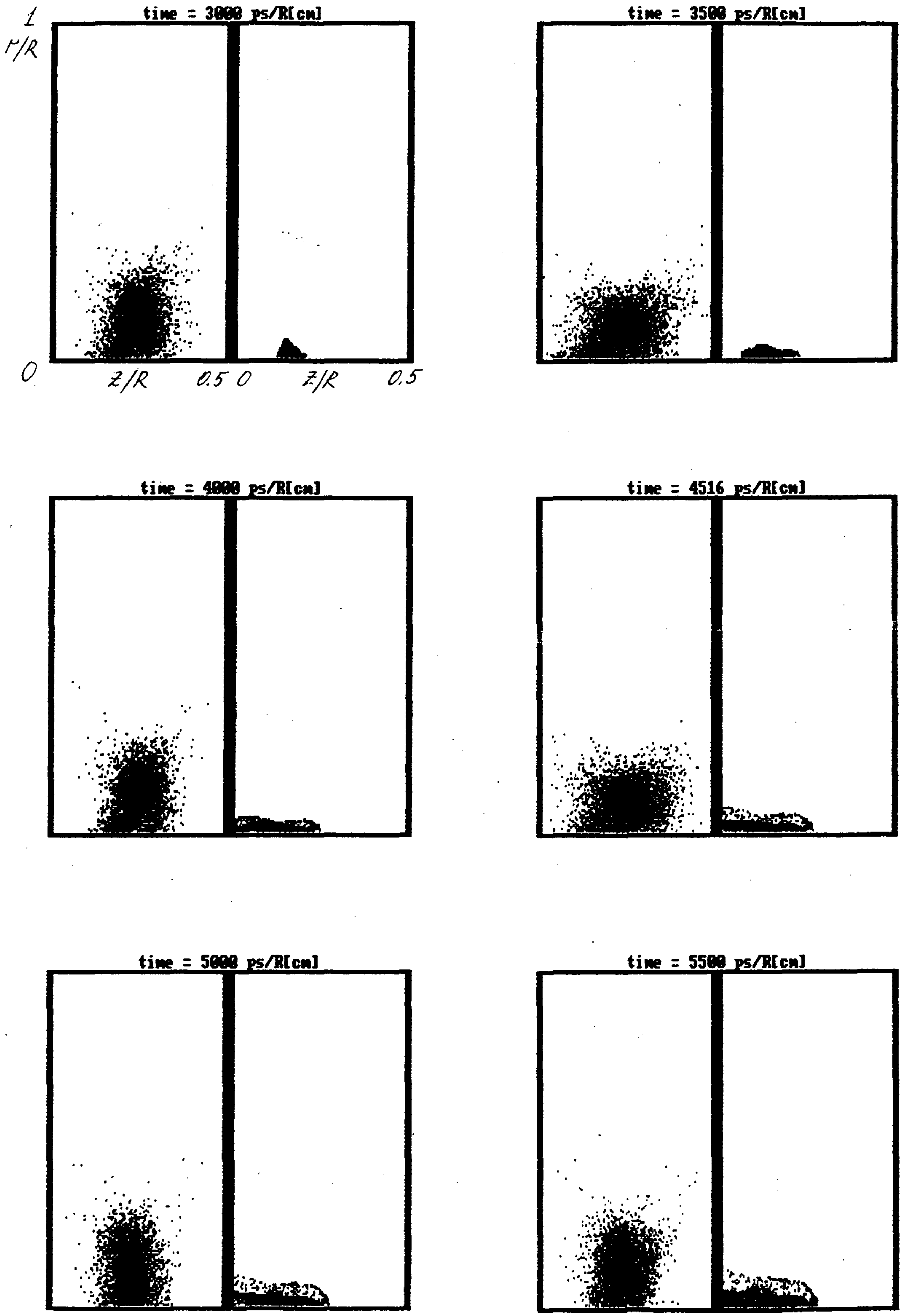
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Fig. 4, 6

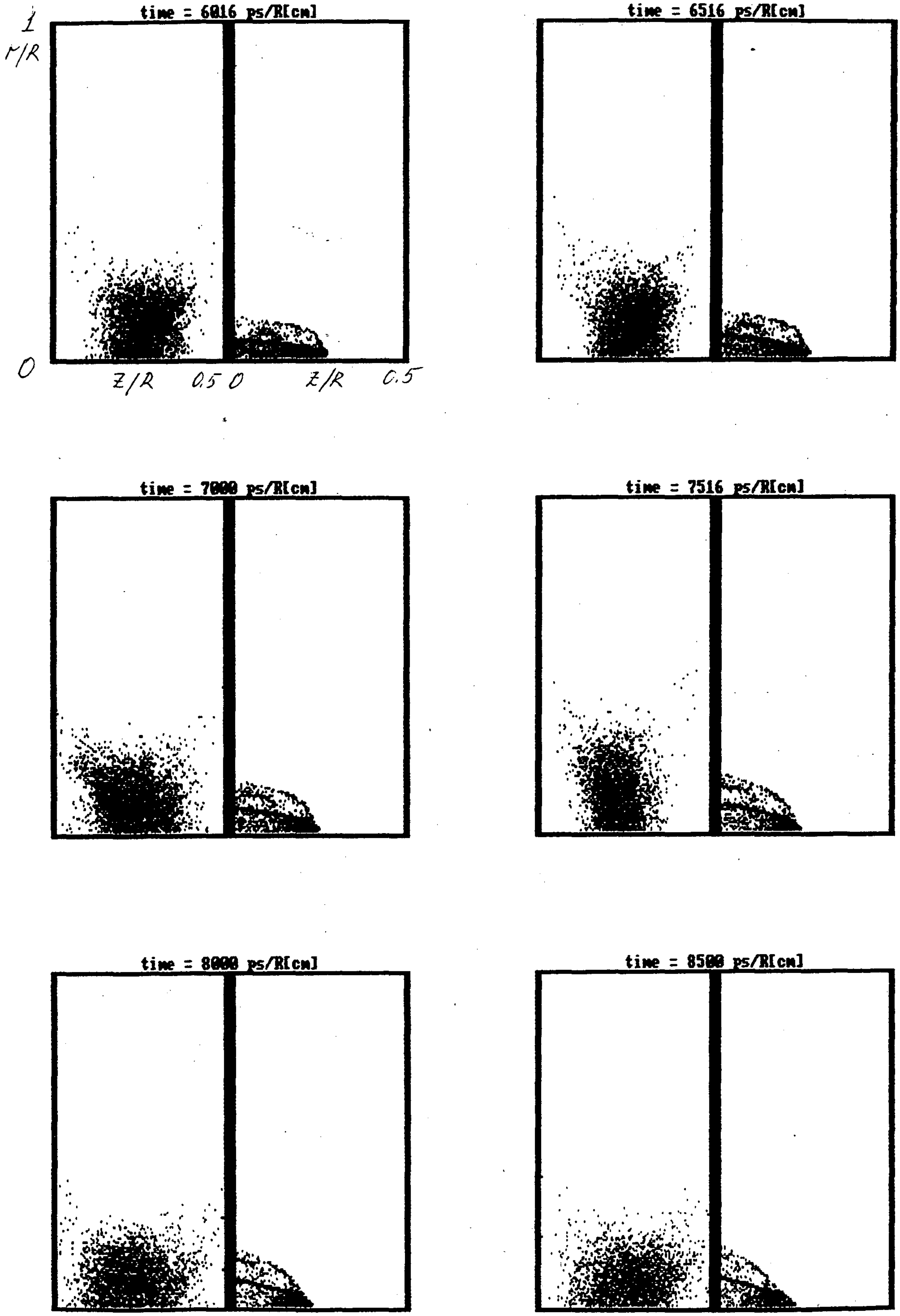
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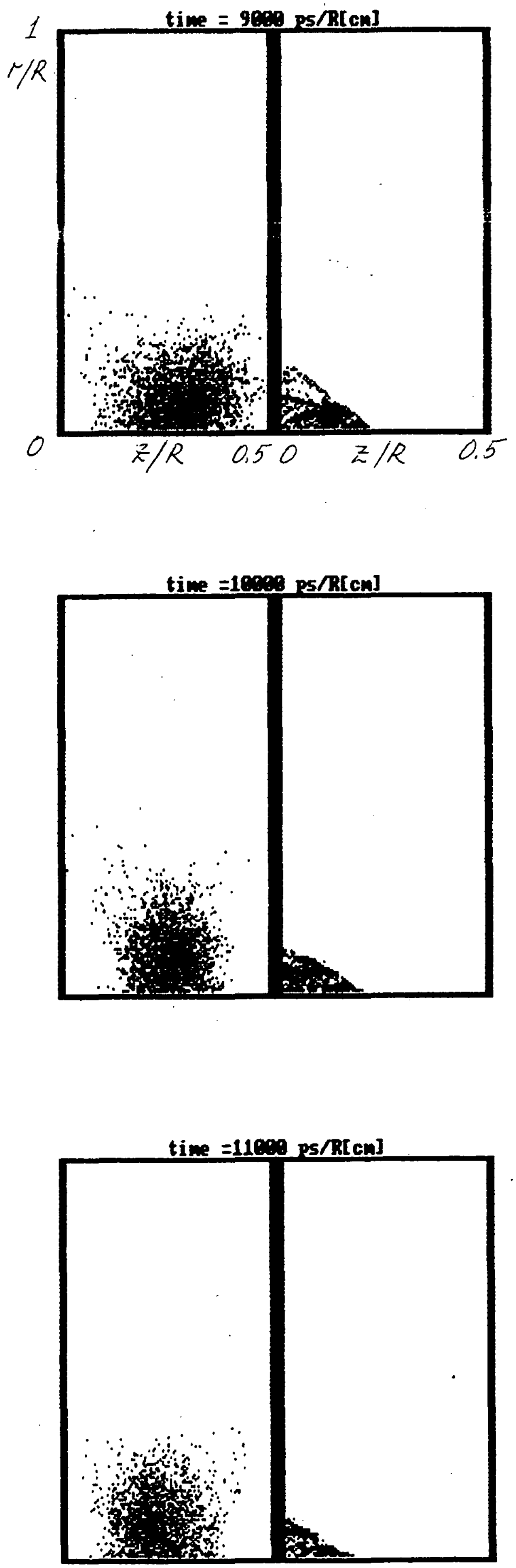
Fig. 4,c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z/R
0.5
time = 9500 ps/R[cm]
time =10000 ps/R[cm]
time =10516 ps/R[cm]
time =11000 ps/R[cm]
time =11500 ps/R[cm]

Fig. 4.d

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