Relativistic Coulomb explosion of spherical microtarget

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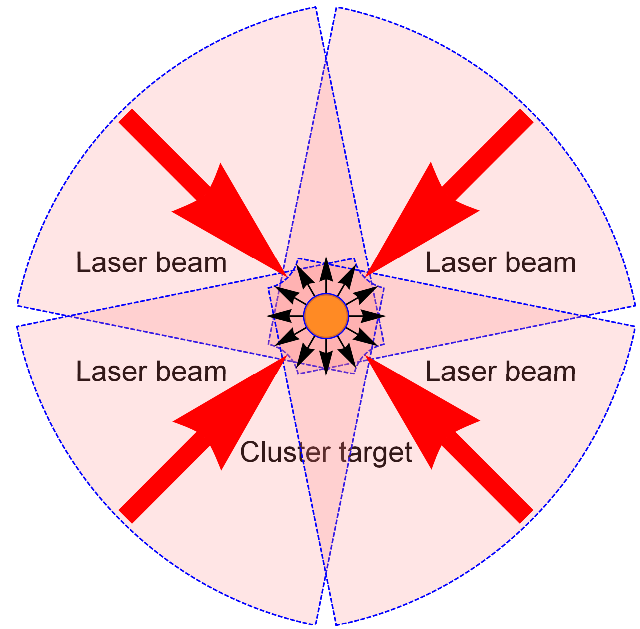
RCE: XCELS realization?

XCELS parameters:

Laser
- beam energy: $\mathcal{E}_L = 300\ J\,;$
- pulse duration: $\tau_L = 25\ fs\,;$
- wavelength: $\lambda_L = 0.91\mu m\,;$
- intensity: $I = 4\mathcal{E}_L/\tau_L \pi D_f^2\,,$

$D_f = 4\mu$m $\Longrightarrow$ $I \sim 9.5\times10^{22}$ W/cm^2

$D_f = 8\mu$m $\Longrightarrow$ $I \sim 2.4\times10^{22}$ W/cm^2



History & motivation:

Theoretical treatment & analytical models:

Nishihara K., Amitani H., Murakami M., Bulanov S.V., Esirkepov T.Zh. Nucl.Instr.Meth. A 464, 98(2001).

Kaplan A.E., Dubetsky B.Y., Shkolnikov P.L. Phys.Rev.Lett., 91, 143401 (2003).

Kovalev V.F., Bychenkov V.Yu. JETP, 101(2), 212 (2005);

Kovalev V.F., Popov K.I., Bychenkov V.Yu., Rozmus W. Phys.Plasmas, 14, 053103 (2007).

RCE: XCELS realization?

CE: small-scale clusters ($\sim 10nm$). Applications.

McPherson A., Luk T.S., Thompson B.D., et.al. Phys.Rev.Lett., 72, 1810 (1994) (XUV + X-ray),

Jahangiri F., Hashida M., Nagashima T., et.al. Appl.Phys.Lett., 99, 261503 (2011) (THz),

Ditmire T., Tisch J.W.G., Springate E., et.al. Nature, 386, 54 (1997) (Th.-nuclear neutrons).

CE: large clusters ($\sim 100 \div 150nm$).

Ter-Avetisyan S., Ramakrishna B., Borghesi M., et.al. Appl. Phys.Lett., 99, 05150 (2011).

Bychenkov V.Yu., Tikhonchuk V.T., Tolokonnikov S.V. JETP, 88(6), 1137 (1999).

Ter-Avetisyan S., Ramakrishna B., Prassad R., et.al. Phys. Plasmas, 19(7), 073112(1-8) (2012).

Laser amplitude $a_E = eE_L/m\omega c$, for RCE conditions

BahkS.-W., Rousseau P., Planchoun T.A., et.al. Opt. Lett., 29, 2837 (2004).

Esirkepov T.Zh., Bingham R., Bulanov S., et.al. Laser and Particle Beams, 18, 503 (2000).

Bulanov S.V., Wilkens Ya.Ya., Esirkepov T.Zh., et.al. Phys.-Usp.,57, 1149 (2014).

Krainov V.P., Smirnov B.M., Smirnov M.B. Phys.- Usp., 50:9, 907 (2007).

Krainov V.P., Smirnov M.B. Phys. Rep., 370,237 (2002).

$$a_E \geq (\omega r_0/c)\sqrt{n_e/n_c}, \quad \Rightarrow \quad r_0 \sim c/\omega_{Li} \quad \Rightarrow \quad a_E \geq 100\,.$$

RCE: XCELS realization?

Rough estimates for cluster radius: $r_{min} \leq r_0 \leq r_{max}$

I. Upper limit r_{max}: energy balance condition

$$\eta b \mathcal{E}_L = (4\pi/3) n_e r_0^3 T_e , \quad \Rightarrow \quad T_e = 1.49 \times 10^{18} \eta b \mathcal{E}_L / n_e r_0^3 \quad \text{in [eV]} ,$$

η – fraction of absorbed energy, b – number of beams, n_e – density in [cm^{-3}] and r_0 in [cm].

CE regime condition $\lambda_D \gg r_0$, where $\lambda_D \approx 7.43 \times 10^2 \sqrt{T_e / n_e}$ in [cm].

Upper limit for cluster radius follows from $\lambda_D \sim r_0|_{r_0 = r_{max}}$,

$$r_0 \leq r_{max} , \quad \text{where} \quad r_{max} \approx 6.1 \times 10^4 \left(\eta b \mathcal{E}_L / n_e^2 \right)^{1/5} \quad \text{in [cm]} .$$

II. Lower limit r_{min}: relativistic level overshoot $\Rightarrow \varepsilon_m \equiv (M/3) \omega_{Li}^2 r_0^2 \geq M c^2$,

$$r_0 \geq r_{min} , \quad \text{where} \quad r_{min} \approx 3.9 \times 10^7 \sqrt{M / Z m_p n_e} \quad \text{in [cm]} .$$

For the XCELS parameters and $n_e = 2 \times 10^{22}$cm^{-3}, $\mu = Z = 1$, we get $r_{min} \approx 2.8 \times 10^{-4}$cm and $r_{max} \approx 2.3 \times 10^{-4} (\eta b)^{1/5}$cm.

Result: 2 var. a) One ion species cluster, r_0 ~2.5 μm, multi-beam configuration, $\eta b > 1$.

b) For $b = 1$ we have $r_0 < r_{min}$, hence, a cluster with two ion species is needed: massive core of heavy ions with Z_1 and n_1, and small amount of impurity ions with Z and n, such that $Zn \ll Z_1 n_1$. Then we get non-relativistic core ions + relativistic impurity ions provided that $\mu = Z M_1 / Z_1 M \gg 1$, where M and M_1 are impurity and heavy ion masses.

RCE: 1-species, homogenous cluster

Cold ions hydrodinamic eqns + Poisson eqn.

$$\partial_t n + r^{-2}\partial_r r^2 n u = 0\,, \qquad \partial_t u + u\partial_r u = \frac{ZeE}{M\gamma^3}\,, \qquad \partial_r r^2 E = 4\pi e r^2 Z n\,,$$

$$n_{|t=0} = n_0(r)\,,\ u_{|t=0} = u_0(r)\,,\ E_{|t=0} = \frac{4\pi e}{r^2}\int_0^r \mathrm{d}y y^2 Z n_0(y)\,,\ \gamma = [1-(u/c)^2]^{-1/2}\,.$$

Initial conditions: $n_0 = n_{c0}\theta(r_0 - r)\,,\ n_{c0} = \mathrm{const},\ u_0 = 0$ – homog. sph. cluster.

Analytical solution (dimensionless variables r/r_0, h/r_0, tr_0/c, u/c)

$$u = \frac{2q\sqrt{\zeta(1+q^2\zeta)}}{1+2q^2\zeta}\,,\ r = \frac{h}{1-q^2}\,,\ 0 \leqslant h \leqslant 1\,,\ n = n_{c0}(1-q^2)^3/A\,,\ \zeta = \zeta_0 h^2\,,\ \zeta_0 = \frac{\omega_{\mathrm{L}}^2 r_0^2}{6c^2}\,,$$

$$A = 1 - \frac{q^2\zeta}{(1+\zeta)^2(1+2\zeta q^2)}\left[3 + 5\zeta q^2 + 2\zeta^2 q^2 + \frac{3(1-q^2)\sqrt{1+\zeta q^2}}{2q\sqrt{1+\zeta}}\ln\frac{\sqrt{1+q^2\zeta} - q\sqrt{1+\zeta}}{\sqrt{1+q^2\zeta}+q\sqrt{1+\zeta}}\right],$$

$$2\sqrt{\zeta_0}\,t = \frac{q}{1-q^2}\sqrt{1+q^2\zeta}\frac{1+2\zeta}{1+\zeta} - \frac{1}{2}(1+\zeta)^{-3/2}\ln\frac{\sqrt{1+q^2\zeta} - q\sqrt{1+\zeta}}{\sqrt{1+q^2\zeta}+q\sqrt{1+\zeta}}\,.$$

Cluster boundary $h = 1$, $r = r_f = 1/(1-q^2)$, $\zeta = \zeta_0$.

Bychenkov, Kovalev, Pis'ma v ZhETF (2011) **94**(2) 101.

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Analytical solution (dimensionless variables r/r_0, h/r_0, tr_0/c, u/c)

Non-relativistic limit , $\zeta \to 0$

$$u = 2\sqrt{\zeta_0}\, q(1-q^2)r\,,\; n = n_{c0}(1-q^2)^3\,,\; 2\sqrt{\zeta_0}\, t = \frac{q}{1-q^2} - \frac{1}{2}\ln\frac{1-q}{1+q}\,, \quad 0 \leqslant r \leqslant \frac{1}{1-q^2}\,.$$

Inside the cluster $u \propto r$, $E \propto r$.

At the cluster boundary $r = r_f = 1/(1-q^2)$, $u_f = 2\sqrt{(1-1/r_f)\zeta_0}$.

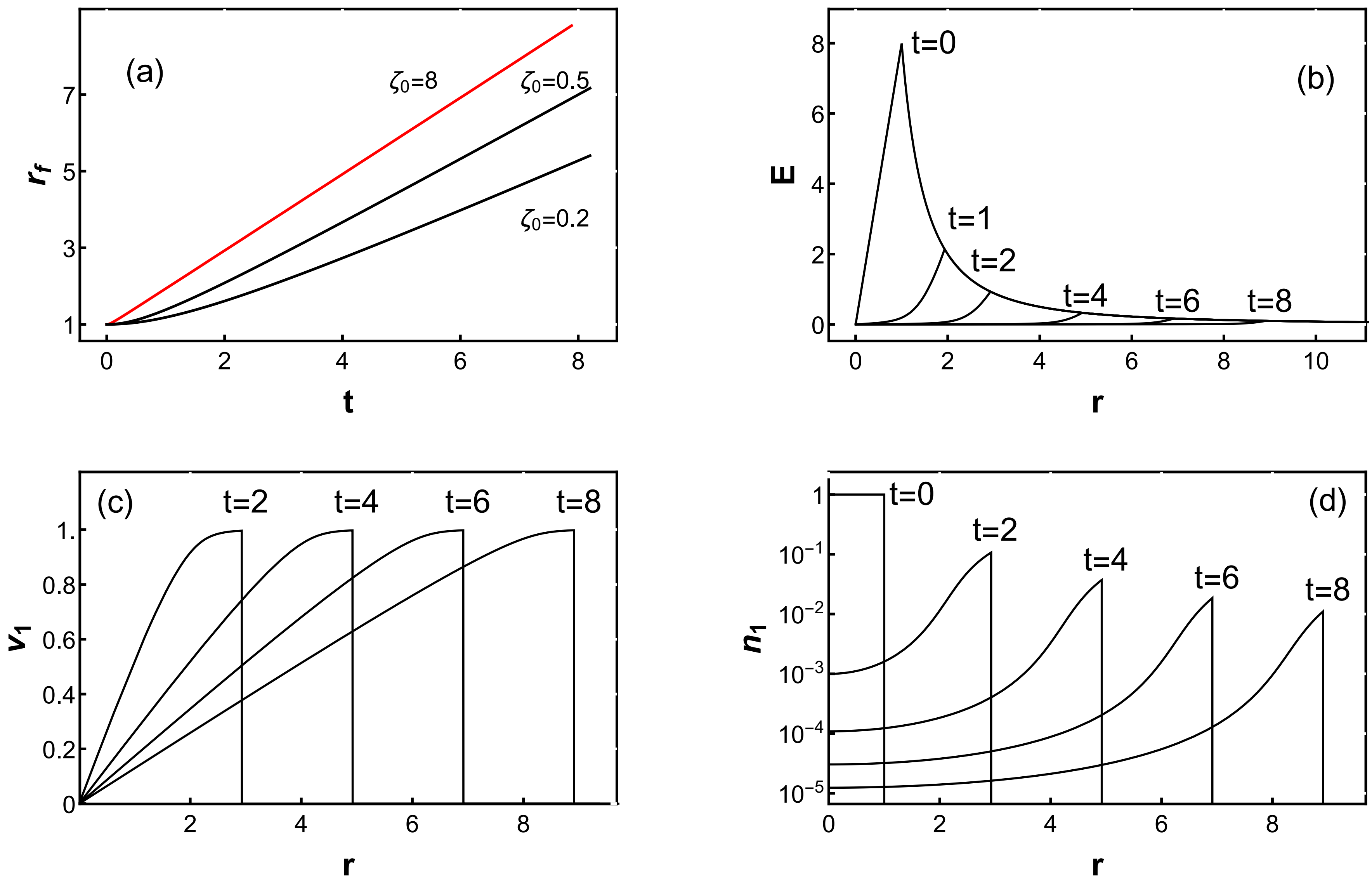
At $t \to \infty$ we get $u \to u_m = 2\sqrt{\zeta_0}$, $\varepsilon_m = 2Mc^2\zeta_0$.

Kaplan, Dubetsky, Shkolnikov, PRL (2003) **91** 143401;

Kovalev, Popov, Bychenkov, Rozmus, PoP (2007) **14** 053103.

RCE: 1-species, homogenous cluster

Spatial-temporal distributions of cluster characteristics



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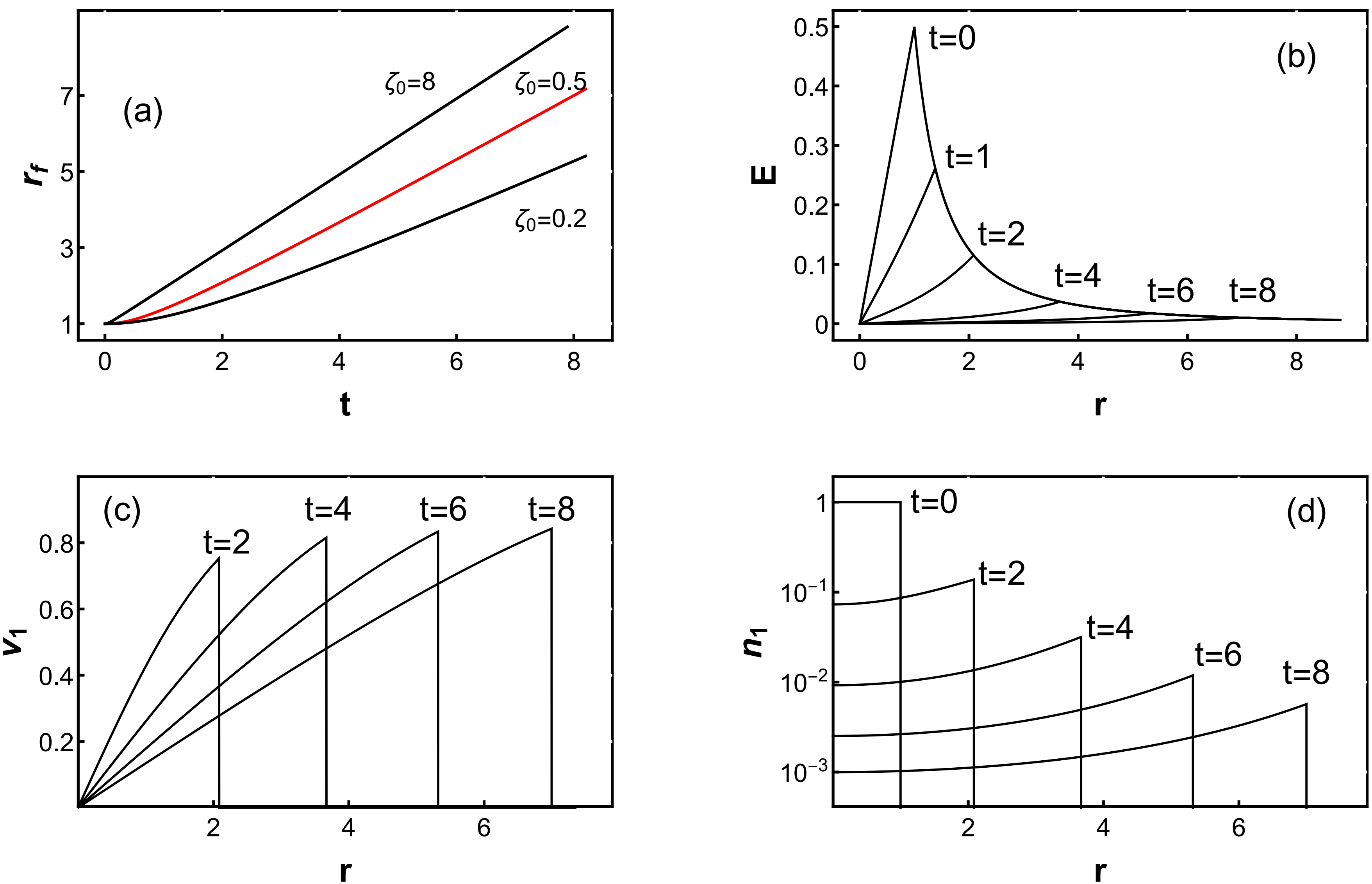

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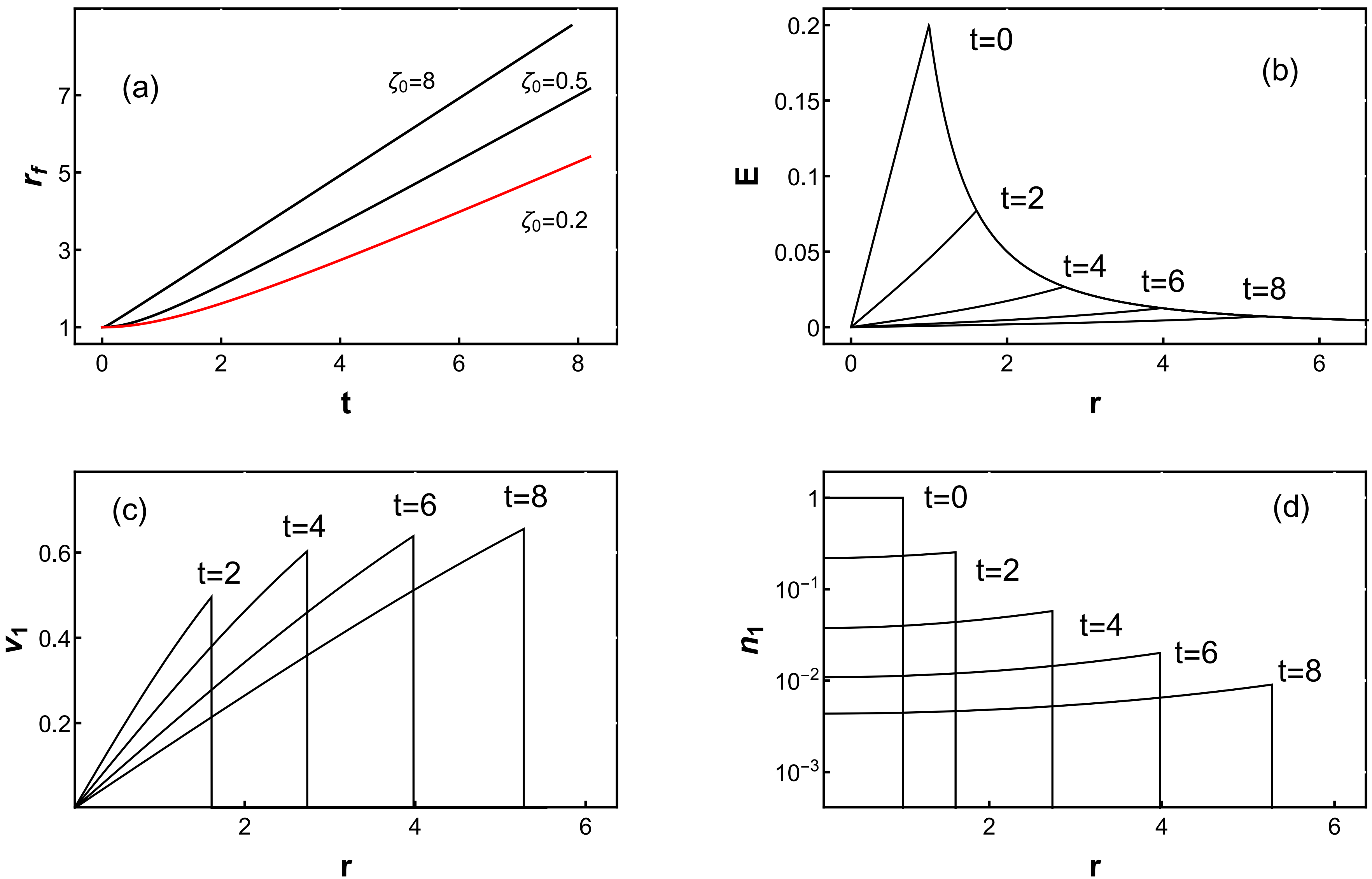

RCE: 1-species, homogenous cluster

Energy of ions and energy spectrum

Ions energy $\varepsilon = 2Mc^2q^2\zeta$ becomes relativistic for $q^2\zeta \sim 1$, i.e. for $t_h \approx \sqrt{2}h/\zeta$.
At the cluster boundary $h = 1$, $\zeta = \zeta_0$, and $t_f \approx \sqrt{2}/\zeta_0$.
For $t \to \infty$ the asymptotic value of ion energy is given by $\varepsilon_m = 2Mc^2\zeta_0 = (M/3)\omega_L^2 r_0^2$.
Spectral distribution of ion energy $N_\varepsilon \equiv \mathrm{d}N/\mathrm{d}\varepsilon$, ($h$ and $q \to$ in terms of ε),

$$N_\varepsilon = \frac{3hr_0}{2Z^2e^2q^2}\left[1 + \frac{1-q^2}{2q^2}(A-1)\right]^{-1}\,,\; N_{\varepsilon\,|_{t\to\infty}} = \frac{3N_0}{2\varepsilon_m^{3/2}}\sqrt{\varepsilon}\,,\; N_0 = \frac{4\pi n_{c0} r_0^3}{3}\,.$$

$$\frac{\delta\varepsilon}{\varepsilon_0} = 1 - \left(1 - \frac{\delta N}{N_0}\right)^{2/3}\frac{q_\delta^2}{q_1^2}\,,\; q_\sigma \equiv q(h = h_\sigma)\,,\; q_1 \equiv q(h=1)\,,\; h_\sigma = (1 - \delta N/N_0)^{1/3}\,.$$

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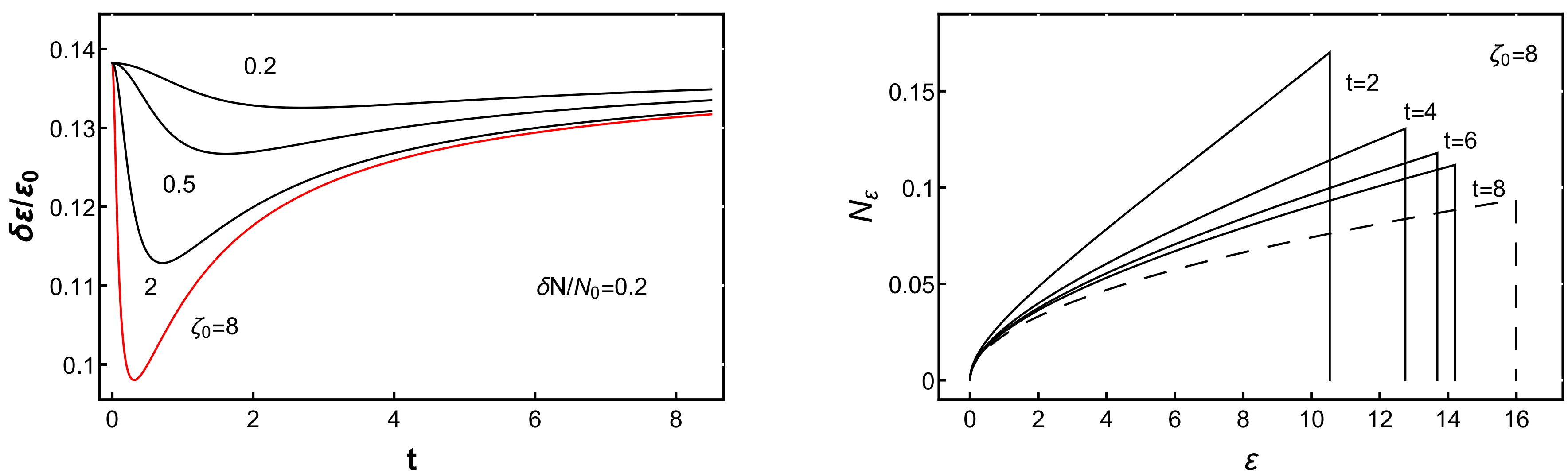

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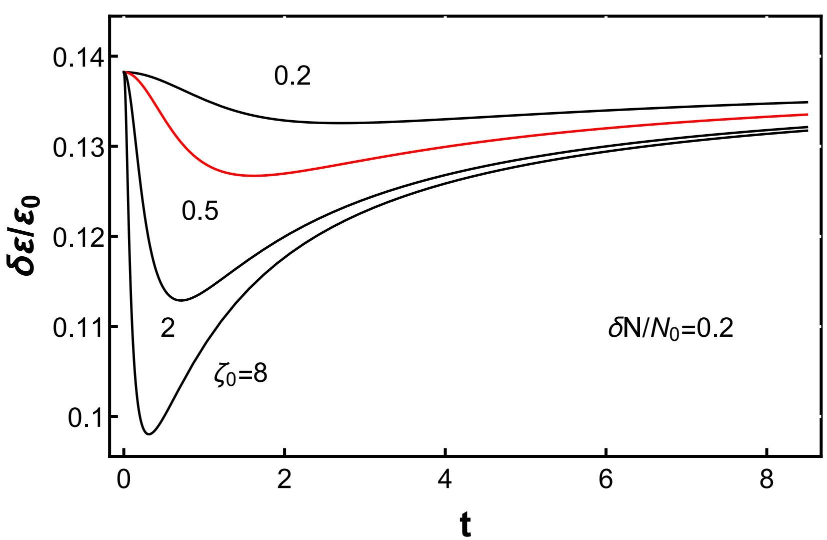

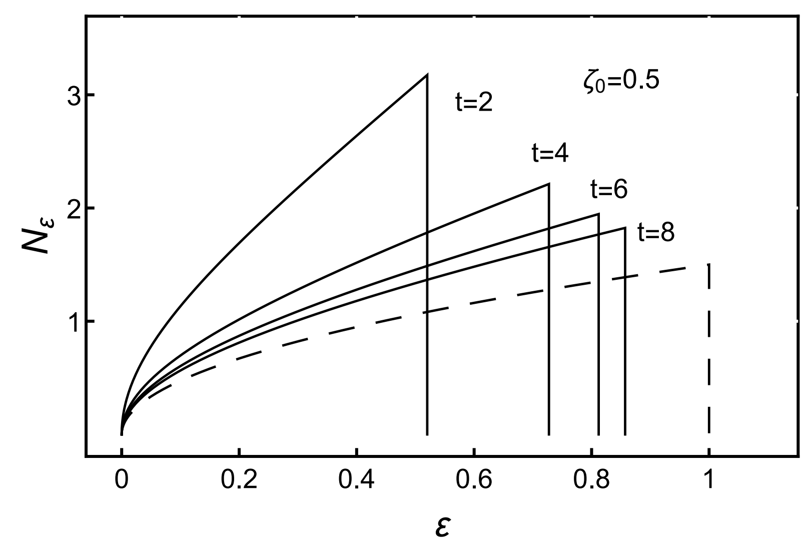

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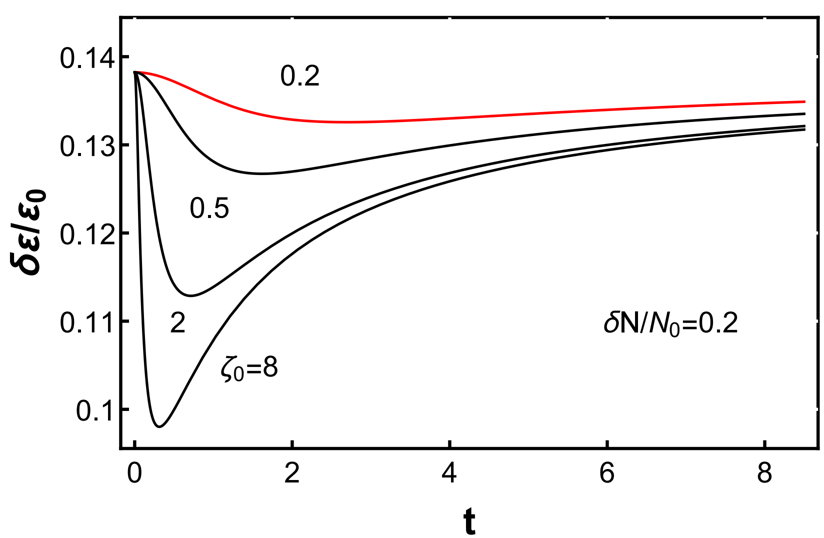

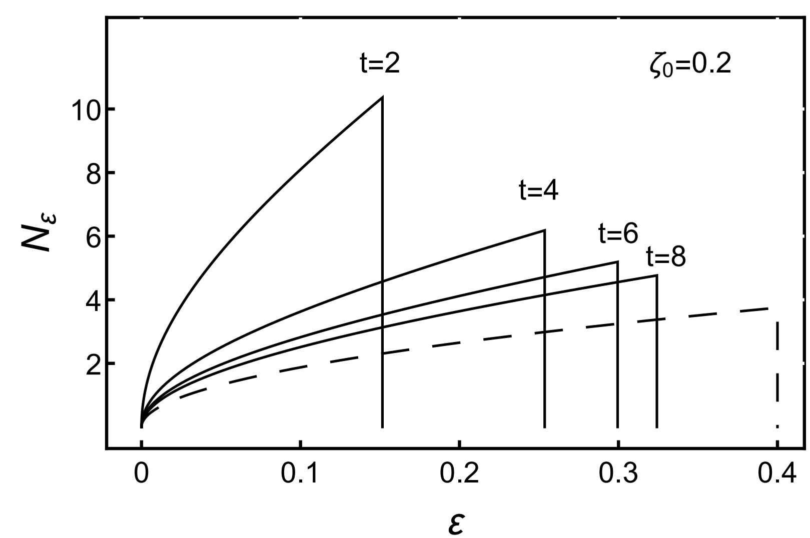

RCE: 2-species, heavy & light ions

Impurity ions dinamics eqns; $Zn \ll Z_1 n_1$, $\mu = ZM_1/Z_1 M$.

$\alpha = 2\mu\zeta_0$, $q_l = Ze$, $Q_h = (4\pi r_0^3/3)Z_1 e n_1$, dimensionless variable $E/(Mc^2/Zer_0)$

$$\begin{cases} \ddot{r} = (1-\dot{r}^2)^{3/2} E(t,r)\,, \\ r_{|t=0} = \rho\,, \quad \dot{r}_{|t=0} \equiv v_{|t=0} = 0\,. \end{cases} \qquad E(t,r) = \alpha \begin{cases} h^3/r^2, & r \leqslant r_f\,; \\ 1/r^2, & r > r_f\,. \end{cases} \qquad \alpha = \frac{Q_h q_l}{Mc^2 r_0}\,.$$

Solution of ion dynamics equations

Bychenkov V.Yu., Kovalev V.F., Andriyash A.V., PlasmaPhysicsReports, 38(11), 879 (2012).

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Solution of ion dynamics equations

a) $r < r_f \Rightarrow t < t_*$, where $r(t_*, \rho) = r_f(t_*) \equiv r_* \Rightarrow$ Numerical methods!

Impurity ion density and velocity $\quad n = \dfrac{\rho^2}{r(\rho,t)^2} \left| \dfrac{\partial r(t,\rho)}{\partial \rho} \right|^{-1}, \qquad v = \dot{r}\,.$

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Solution of ion dynamics equations

b) $r > r_f \Rightarrow t > t_* \Rightarrow$ Analitycal solution

$$t - t_* = \frac{1}{d}\left(\alpha/r_* + (1-v_*^2)^{-1/2}\right)\left(\sqrt{\alpha^2 + br + dr^2} - \sqrt{\alpha^2 + br_* + dr_*^2}\right)$$

$$-\left(\frac{\alpha}{\sqrt{d}} + \frac{b}{2d^{3/2}}\left(\alpha/r_* + (1-v_*^2)^{-1/2}\right)\right) \ln \frac{2\sqrt{d(\alpha^2 + br + dr^2)} + 2dr + b}{2\sqrt{d(\alpha^2 + br_* + dr_*^2)} + 2dr_* + b}\,,$$

$$v = \left\{1 - \left[(1-v_*^2)^{-1/2} + \alpha\left((1/r_*) - (1/r)\right)\right]^{-2}\right\}^{1/2}\,,\; b = -2\alpha\left(\alpha/r_* + (1-v_*^2)^{-1/2}\right)\,,$$

$$d = -1 + (1-v_*^2)^{-1} + (2/r_*)\alpha\left((1/2r_*)\alpha + (1-v_*^2)^{-1/2}\right)\,.$$

Ion kinetic energy $\varepsilon \equiv -1 + 1/\sqrt{1-v^2} = (1-v_*^2)^{-1/2} + \alpha\,(1/r_* - 1/r)$.
Upper limit of ion energy at $t \to \infty$ and $r \gg r_*$ depends upon ρ,

$$\varepsilon_m(\rho) = \varepsilon(\rho)_{|t\to\infty} = -1 + (1-v_*^2)^{-1/2} + \alpha/r_*\,,\; \varepsilon_{max} \equiv \varepsilon_m(\rho_{max})\,.$$

RCE: 2-species, immobile core ions

Impurity ions dinamics equations: $r_f = 1.$

$$\ddot{r} = \alpha(1-\dot{r}^2)^{3/2} \begin{cases} r, & r \leqslant 1\,; \\ 1/r^2, & r > 1\,. \end{cases} \quad r_{|t=0} = \rho\,, \quad \dot{r}_{|t=0} \equiv v_{|t=0} = 0\,.$$

Moment t_* of impurity ions crossing the cluster boundary

$$t_* = \frac{1}{\sqrt{\alpha}} F\left(\varphi_1, k_1\right) - \frac{2}{\sqrt{\alpha}} E\left(\varphi_1, k_1\right) + \frac{\sin^2 \varphi_1}{\sin \varphi_2}\,, \qquad \rho < 2/\sqrt{\alpha}\,,$$

$$t_* = \frac{2}{\rho\alpha} F\left(\varphi_2, k_2\right) - \rho E\left(\varphi_2, k_2\right) + \sin \varphi_2\,, \qquad \rho > 2/\sqrt{\alpha}\,,$$

$$\varphi_1 = \arcsin \sqrt{1-\rho^2}\,, \quad \varphi_2 = \arcsin \sqrt{\frac{1-\rho^2}{1-\rho^2+4/\alpha}}\,;$$

$$k_1 = \sqrt{1-\rho^2\alpha/4}\,, \quad k_2 = \sqrt{1-4/(\rho^2\alpha)}\,.$$

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Solution of ion dynamics equations (inside the cluster $r < 1$, $t < t_*$)

$$t = \frac{1}{\sqrt{\alpha}} F\left(\varphi, k_1\right) - \frac{2}{\sqrt{\alpha}} E\left(\varphi, k_1\right) + \sqrt{(1-\rho^2/r^2)(r^2-\rho^2+4/\alpha)}\,, \quad \rho < 2/\sqrt{\alpha}\,,$$

$$t = \frac{2}{\rho\alpha} F\left(\psi, k_2\right) - \rho E\left(\psi, k_2\right) + r\sqrt{\frac{r^2-\rho^2}{r^2-\rho^2+4/\alpha}}\,, \quad \rho > 2/\sqrt{\alpha}\,,$$

$$\varphi = \arcsin\sqrt{r^2-\rho^2}\,, \quad \psi = \arcsin\sqrt{\frac{r^2-\rho^2}{r^2-\rho^2+4/\alpha}}\,,$$

$$v = \left\{1 - \left[1 + (\alpha/2)\left(r^2-\rho^2\right)\right]^{-2}\right\}^{1/2}\,.$$

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Solution of ion dynamics equations (outside the cluster $r > 1$, $t > t_*$)

$$t - t_* = \frac{\alpha}{2d_\infty}\left(3-\rho^2+2/\alpha\right)\left(\sqrt{\alpha^2+b_\infty r+d_\infty r^2} - \sqrt{\alpha^2+b_\infty+d_\infty}\right)$$
$$+\,\alpha \ln \frac{2\sqrt{d_\infty(\alpha^2+b_\infty r+d_\infty r^2)}+2d_\infty r+b_\infty}{2\sqrt{d_\infty(\alpha^2+b_\infty+d_\infty)}+2d_\infty+b_\infty}\,,$$
$$v = \left\{1-\left[1+(\alpha/2)\left(3-\rho^2-2/r\right)\right]^{-2}\right\}^{1/2}\,,$$
$$b_\infty = -\alpha^2\left(3-\rho^2+2/\alpha\right)\,,\quad d_\infty = -1+(\alpha^2/4)\left(3-\rho^2+2/\alpha\right)^2\,.$$

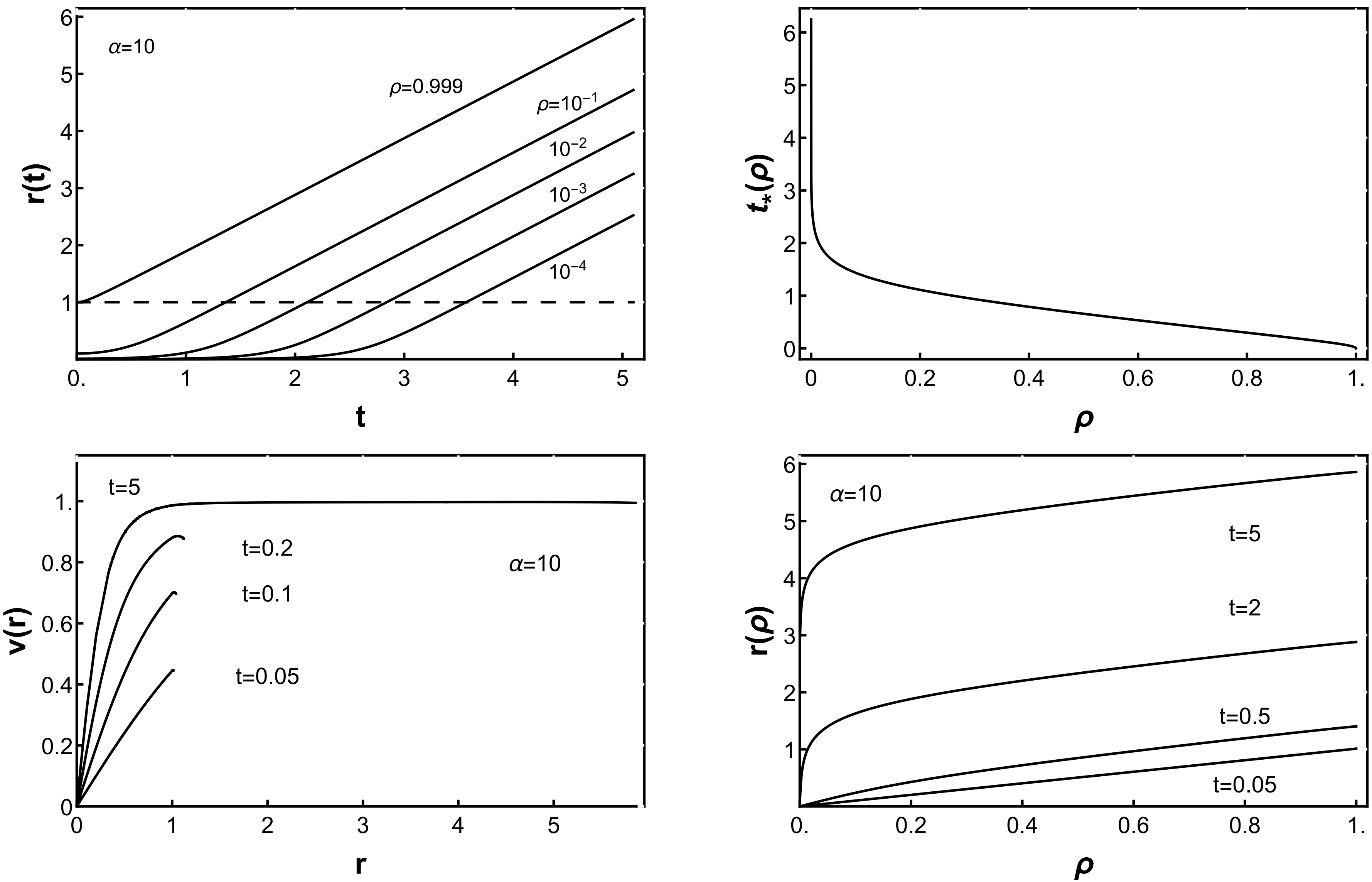
Ion kinetic energy: $\varepsilon = (\alpha/2)\left(3-\rho^2-2/r\right)$, $\varepsilon_m(\rho) = (\alpha/2)\left(3-\rho^2\right)$, $\varepsilon_{max} = (3/2)\alpha$.

Impurity ions energy spectrum:

$$\frac{\mathrm{d}N}{\mathrm{d}\varepsilon} = 3\,\frac{r(\varepsilon)^2 n(t,r(\varepsilon))}{|\;\partial\varepsilon/\partial r\;|}\,.$$

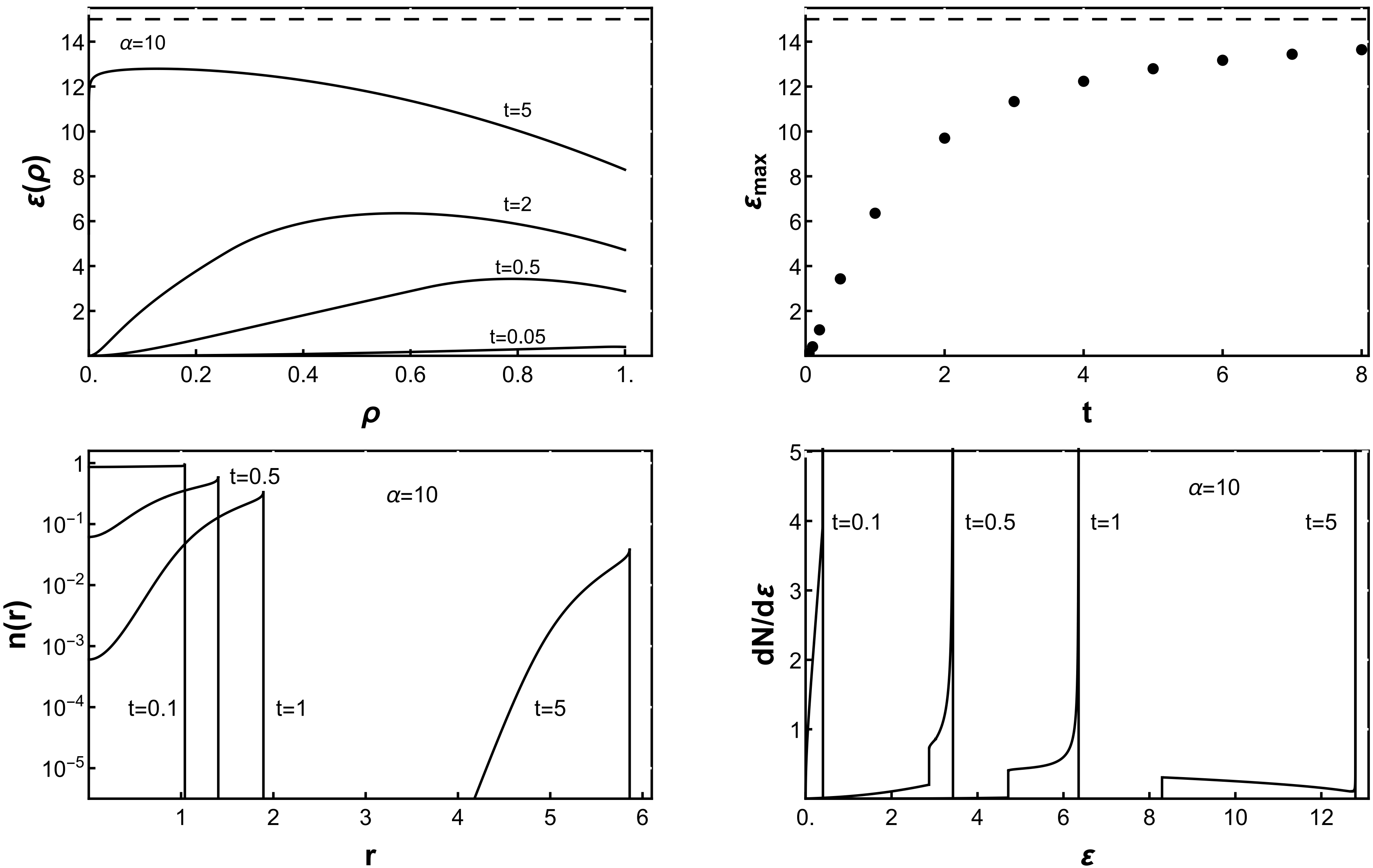
RCE: 2-species, immobile core ions

Spatial-temporal distributions of cluster characteristics



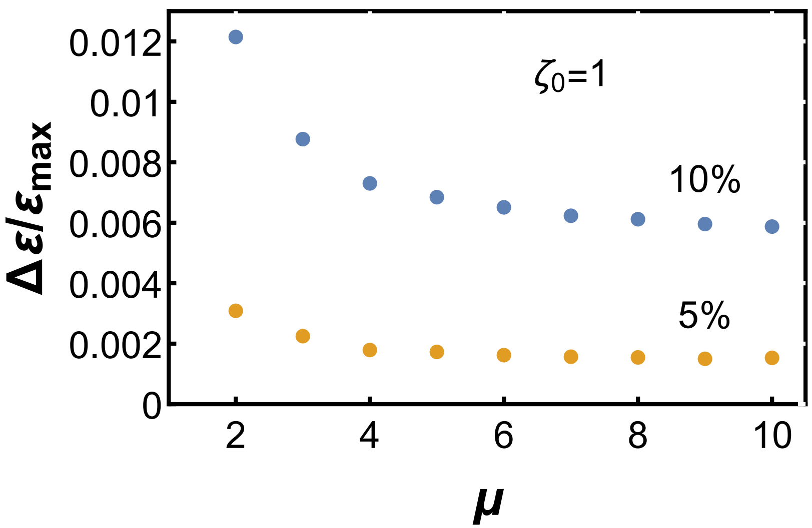
RCE: 2-species, immobile core ions

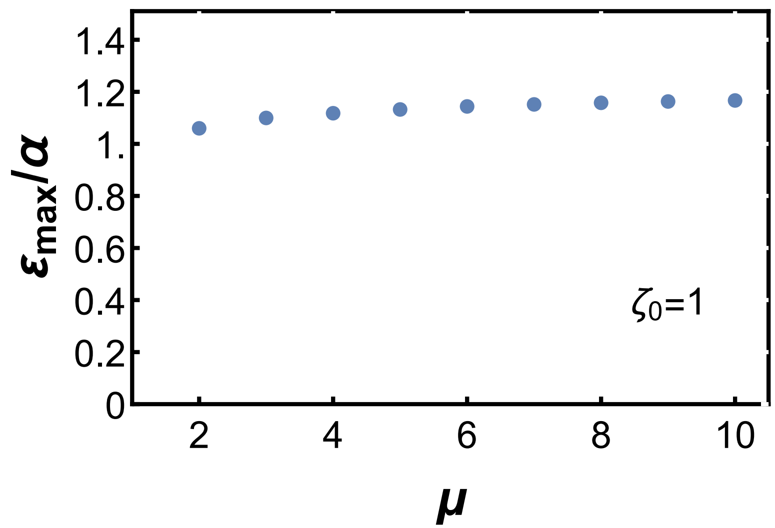
Spatial-temporal distributions of cluster characteristics



RCE: 2-species, choice of parameters

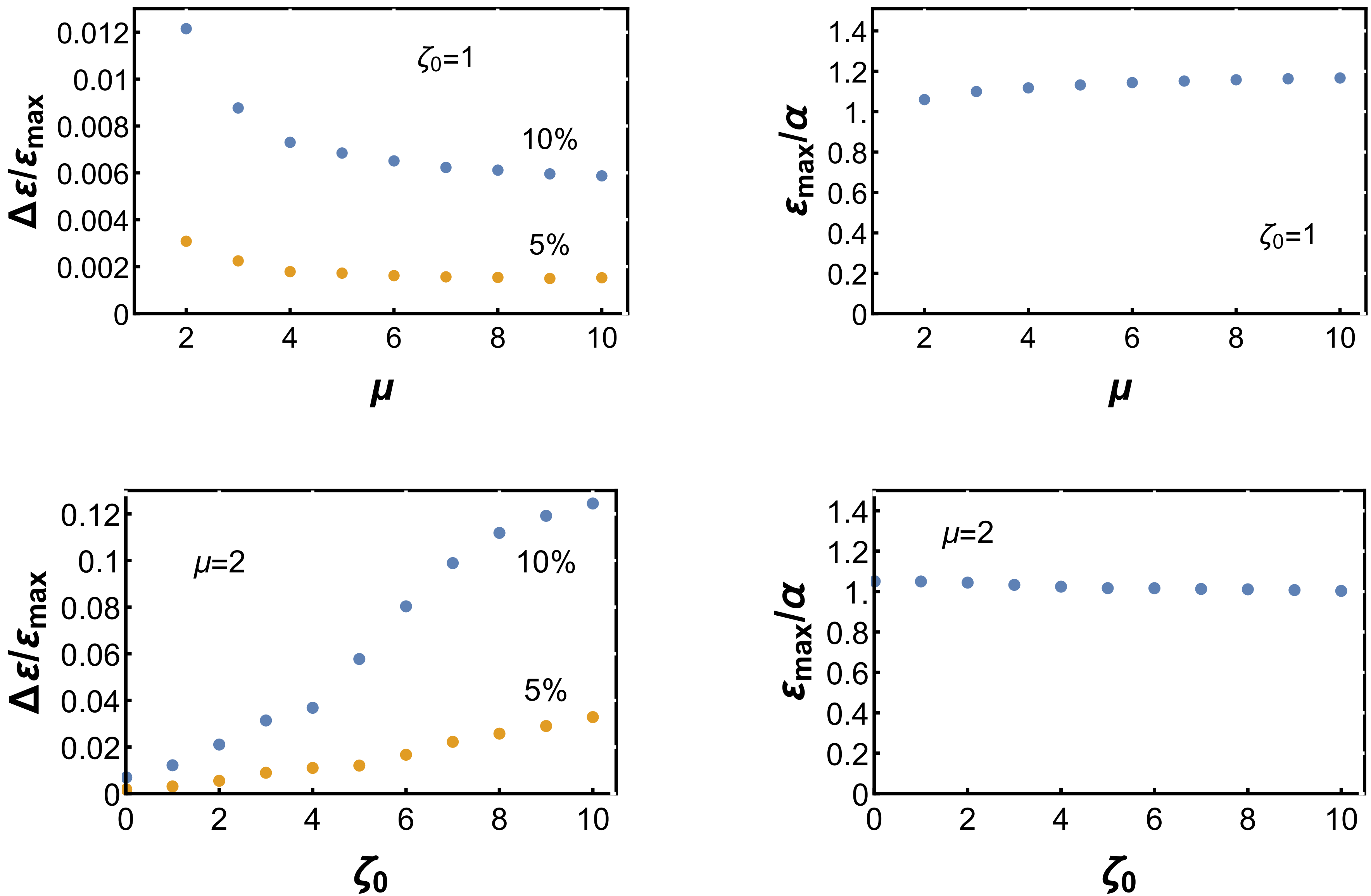
Optimal parameters for impurity acceleration





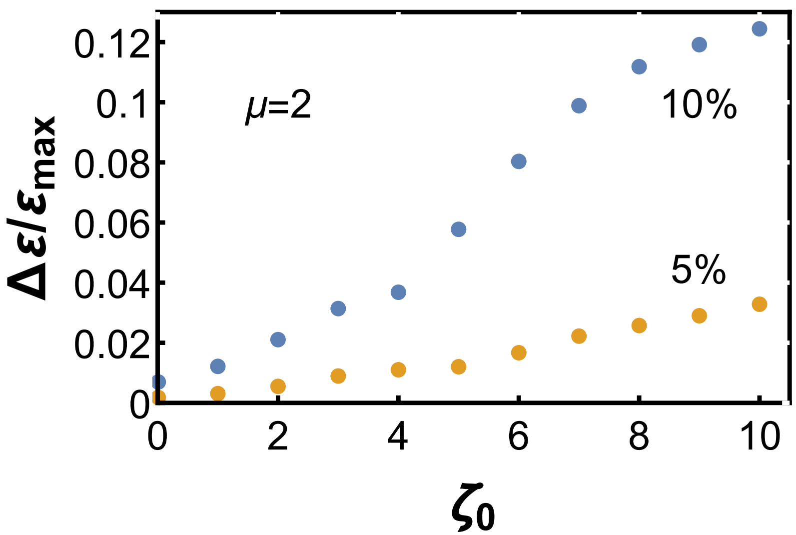
RCE: 2-species, choice of parameters

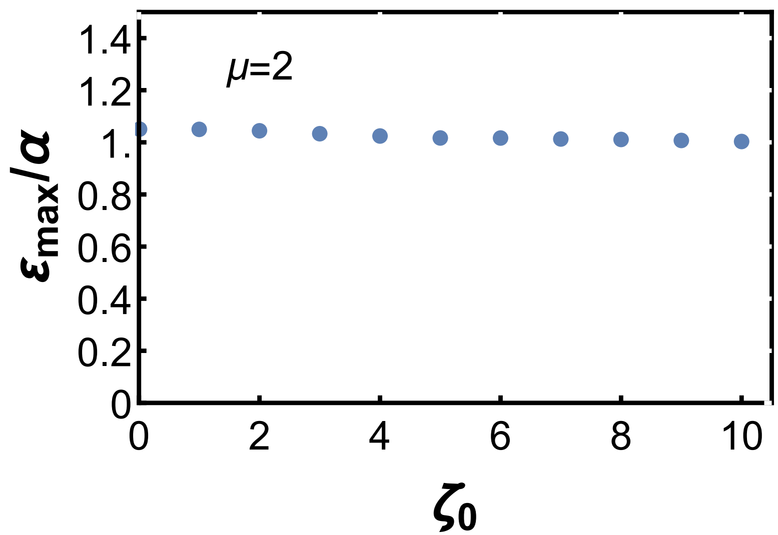
Optimal parameters for impurity acceleration

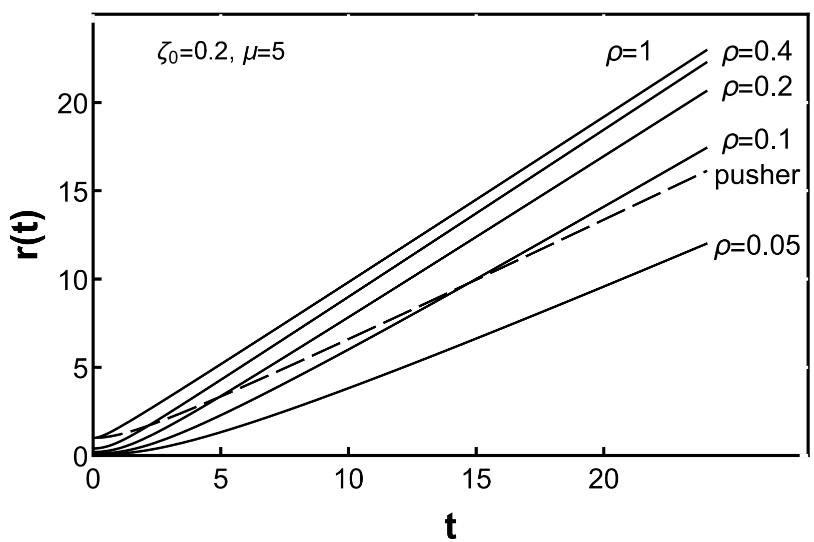


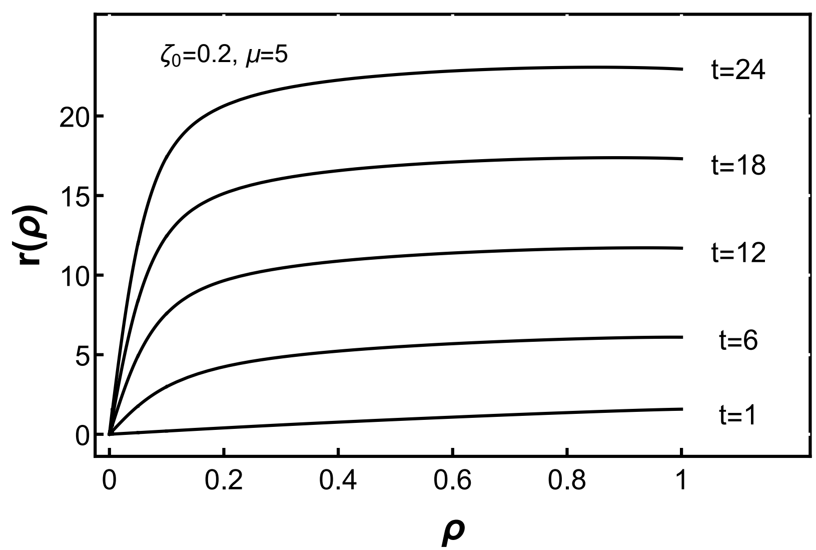
RCE: 2-species, choice of parameters

Optimal parameters for impurity acceleration



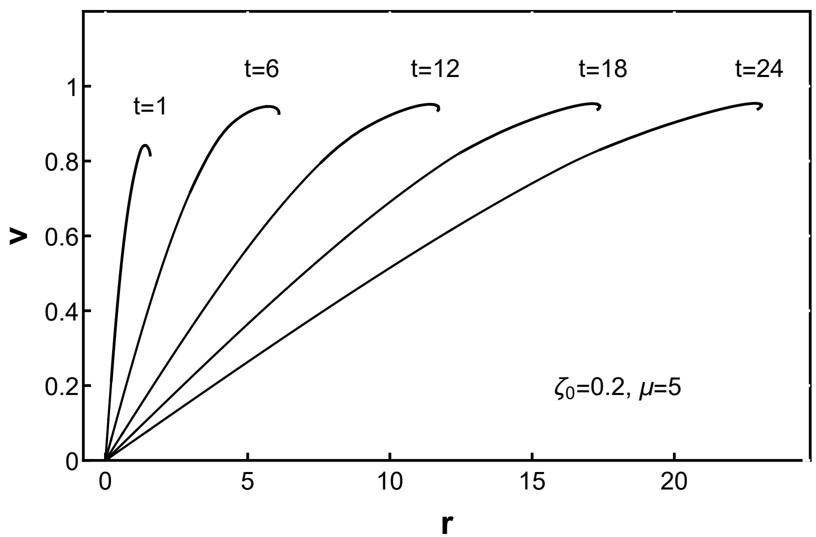


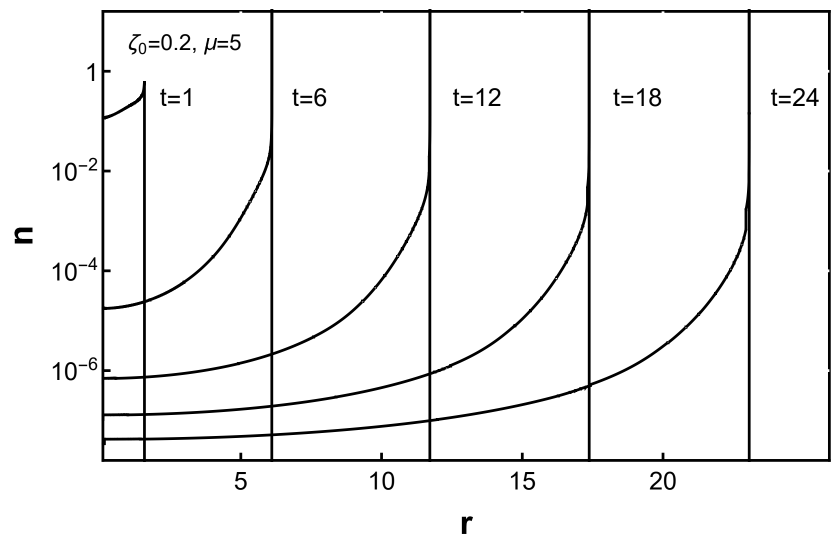


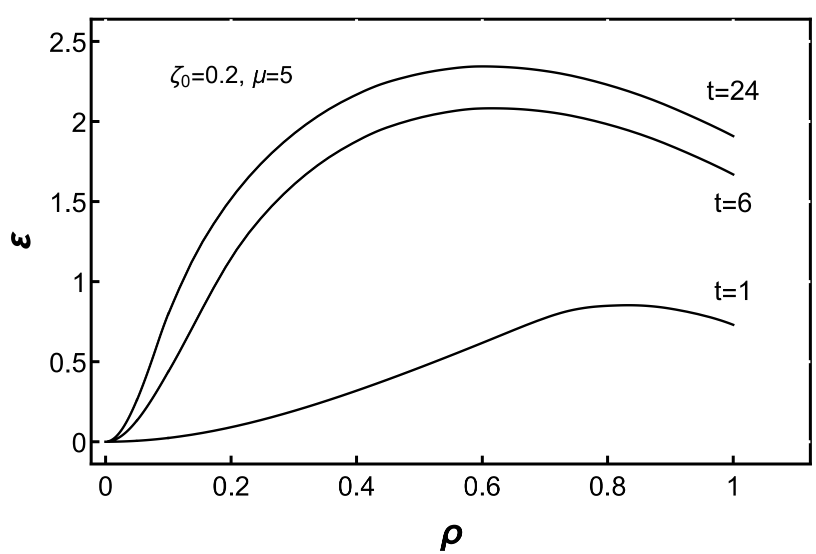


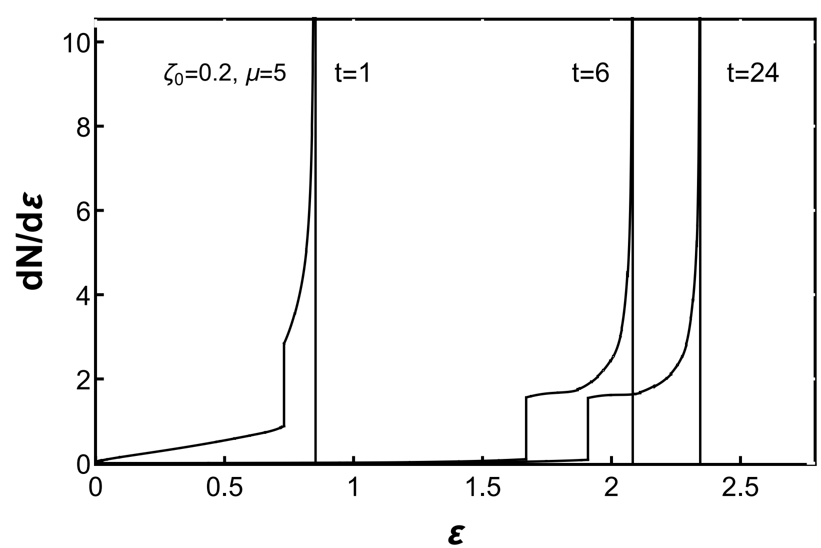
RCE: 2-species, choice of parameters

Optimal parameters for impurity acceleration









Conclusion

- For the XCELS laser facility, generating ultrashort pulses of a record power of laser radiation, the prospect of obtaining particles with energies reaching gigaelectronvolts using the Coulomb explosion of laser-irradiated spherical microtargets is studied.
- A theoretical justification is given for the possibility of experimental realization of the relativistic Coulomb explosion mode of large spherical targets of micron and submicron size using multilateral irradiation by several laser channels. The proposed experiment is substantiated by the results of theoretical (numerical and analytical) studies of the ion acceleration process in a relativistic Coulomb explosion of microtargets consisting either of ions of the same type or of a set of light (impurity) ions and the main heavy ions.
- The space-time and spectral characteristics of accelerated ions with relativistic energy and quasi-monochromatic spectrum are found. The presented study makes it possible to predetermine the characteristics of record-breaking energy ions from spherical microtargets exploding in a Coulomb manner and to provide theoretical support for the experiment on the XCELS laser in single-beam and multi-beam modes.

T H A N K Y O U! Q U E S T I O N S ?