High-energy particle generation from short laser pulses interaction with plasmas

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in collaboration with

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Outline

- PIC simulations

Fully relativistic 2D PIC simulation of fast particle generation in the interaction of ultrashort laser pulses with dense targets with preplasma conditions. Few(several)-cycle laser pulses with single-wavelength spot size.

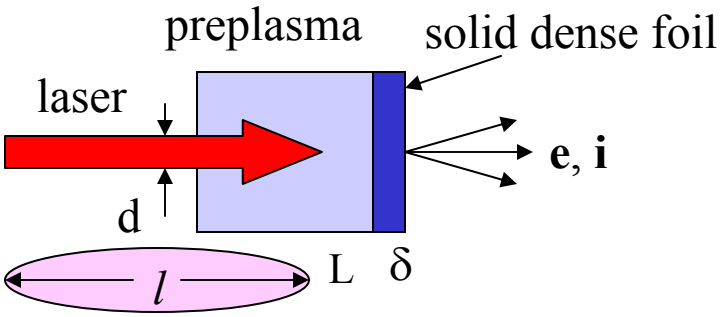
- Vlasov-Poisson numeric model

Two-electron-temperature (Boltzmann) model. Long laser pulses (hundred -- few hundreds fs). Multi-ion species plasma.

- Analytics

Quasi-neutral plasma expansion. After pulse particle acceleration. Effect of the adiabatic particle cooling.

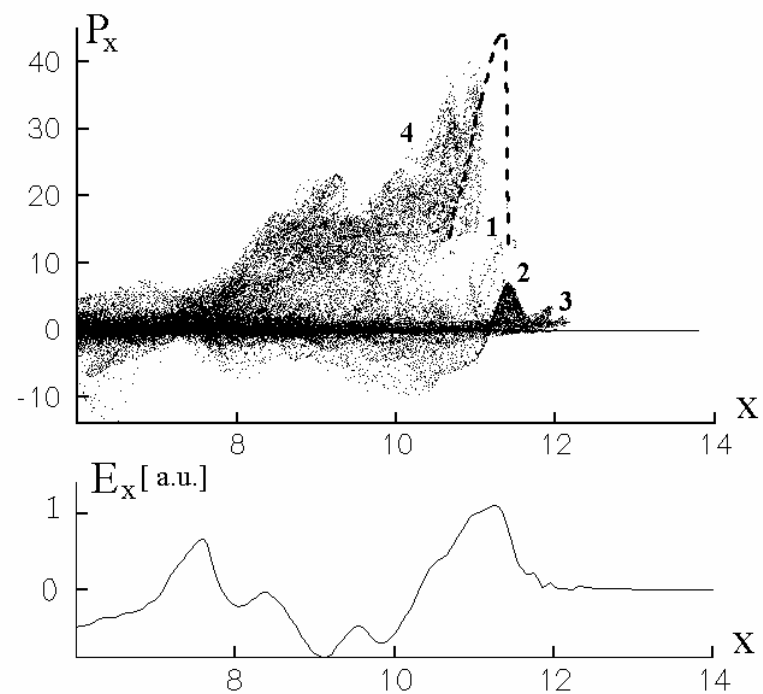
Particle acceleration by few-cycle laser pulses with single-wavelength spot size



$I\,\lambda^2 = 5.5\,10^{18}$-$7.10^{19}$ W/cm^2 μm^2, (a=2-7)
d=(1-2) λ, L=(2-10) λ, *hydrogen,*
δ=(0.25-3) λ, *l*=(1.5-12) λ

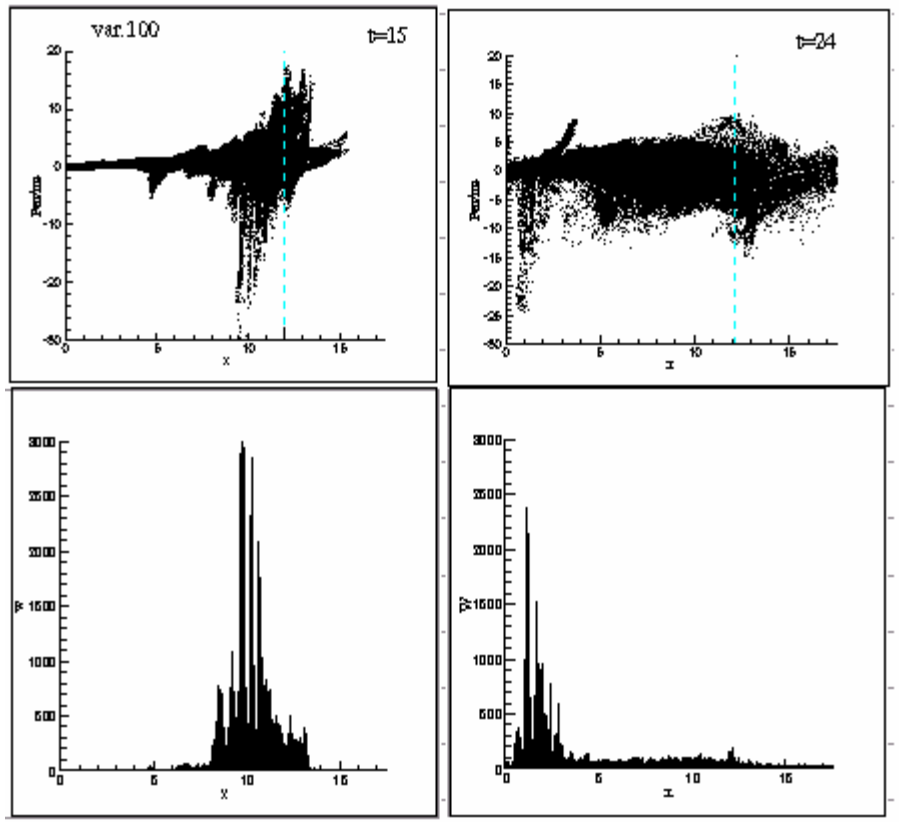
CUOS short-pulse laser

The global characteristics of laser triggered electrons were obtained (in terms of laser and plasma parameters)

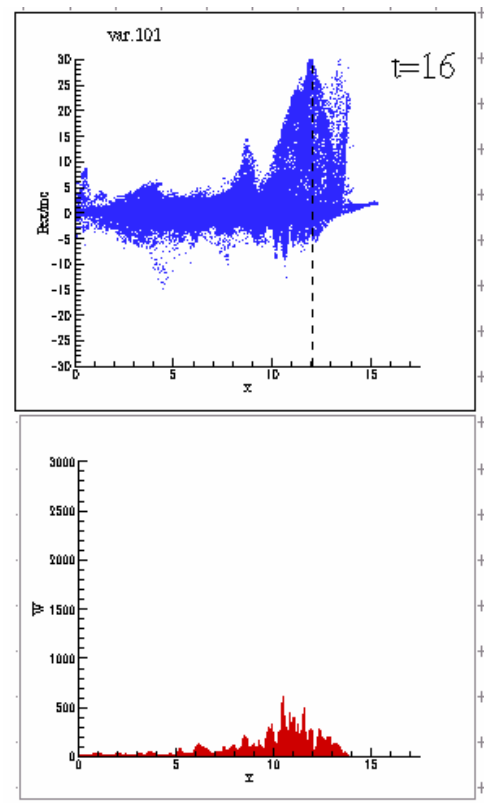


The optimum conditions for forward electron generation were defined as those where electrostatic acceleration at the backside of laser pulse dominates

Backward and forward accelerated electrons



a=7
d=2
l=3

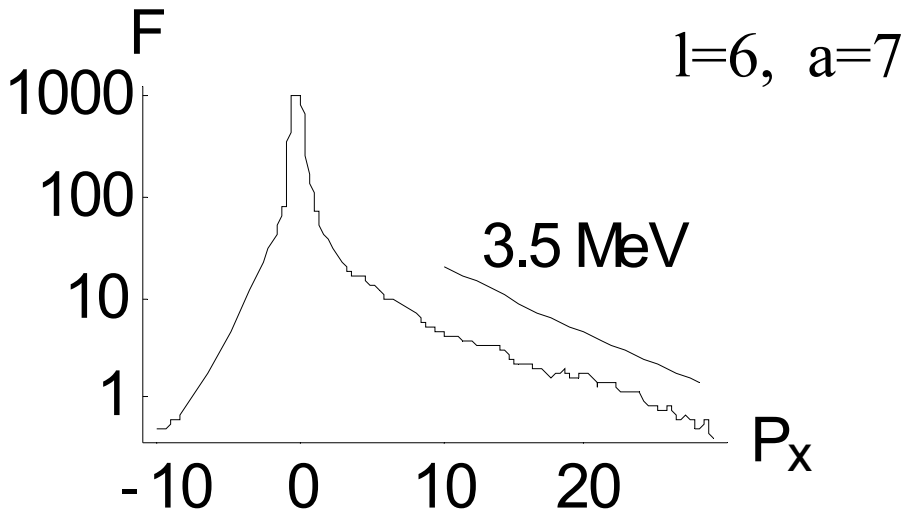


L=2

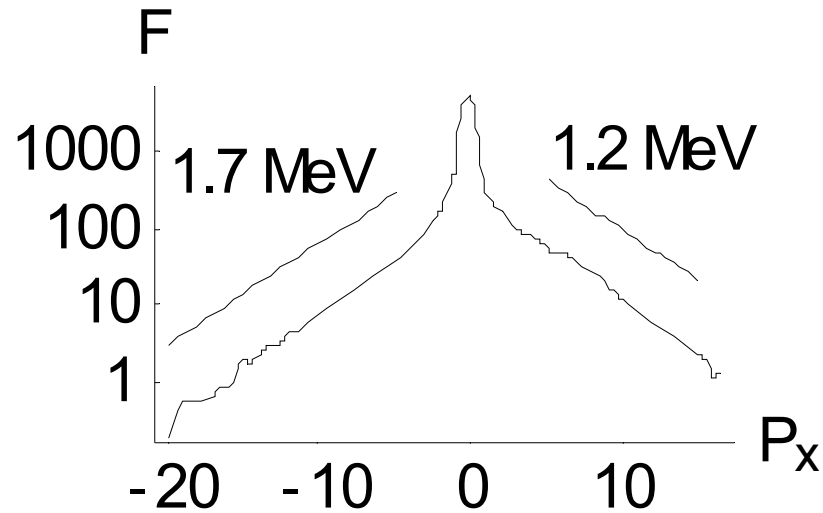
L=5

Long preplasma prevents backward electrons and provides with higher forward electron energy

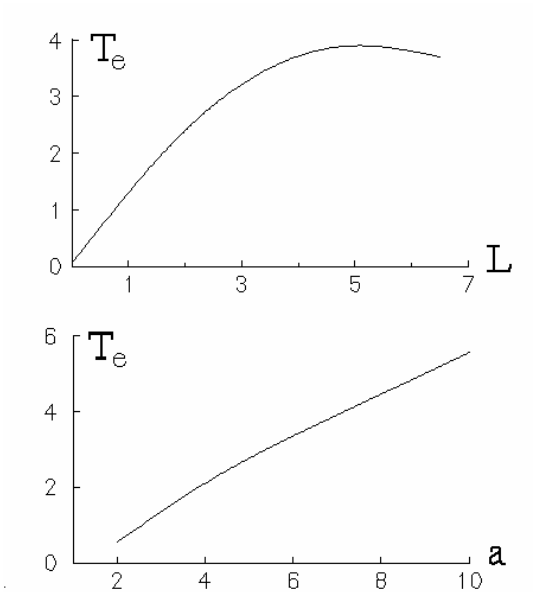
Electron distribution functions



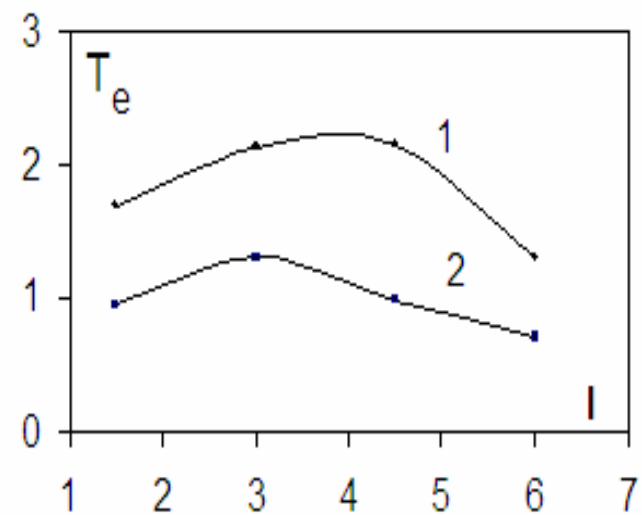
Forward acceleration



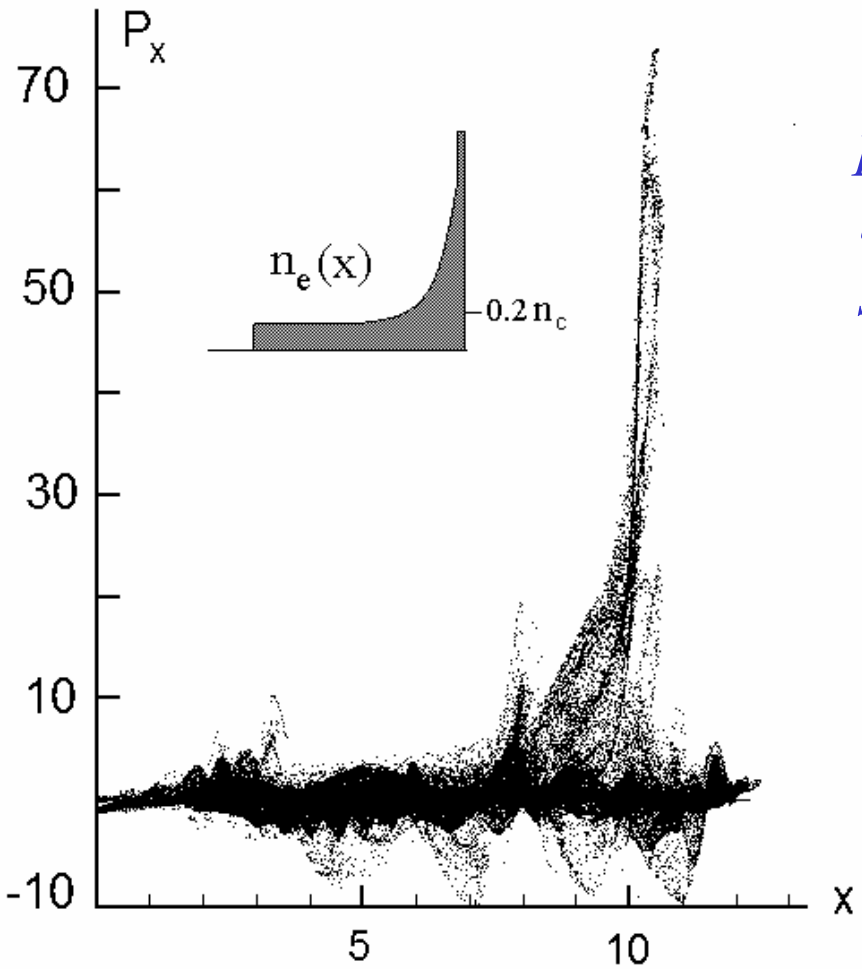
Backward acceleration



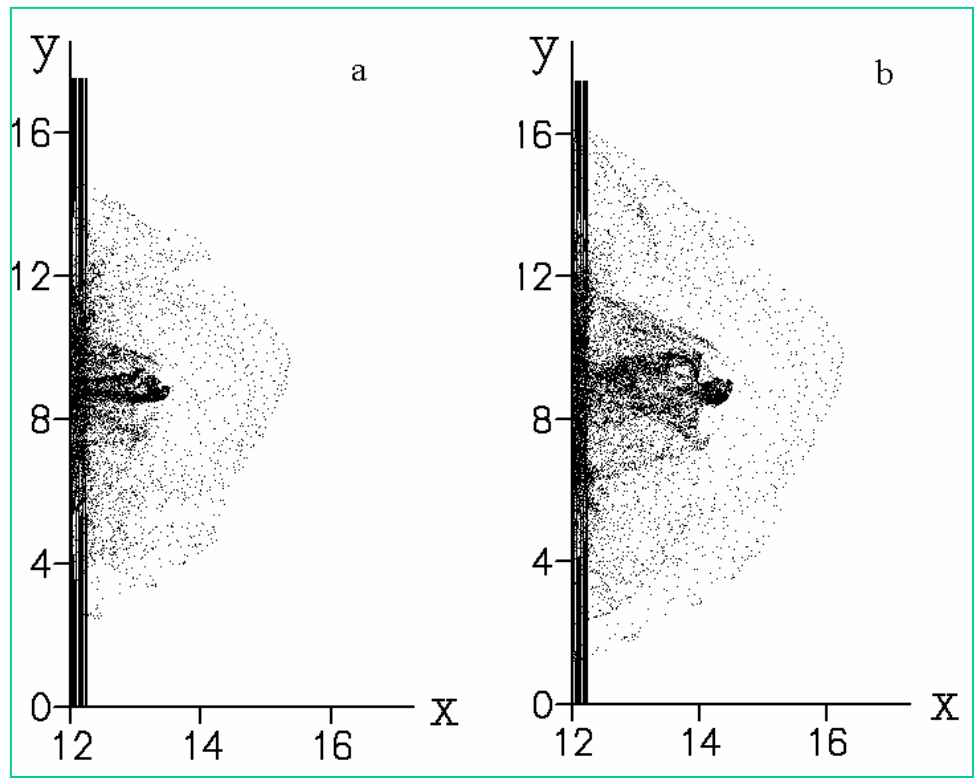
There is an optimum for electron energy at L ~ 2 *l*.
L>> *l* laser energy losses in extended preplasma.
L< *l* electron acceleration length is not enough.



Target design



The target design for effective electron production is shown to be very important issue requiring preplasma size longer than pulse width



Tailoring of the plasma density profile is an effective way to increase electron energy

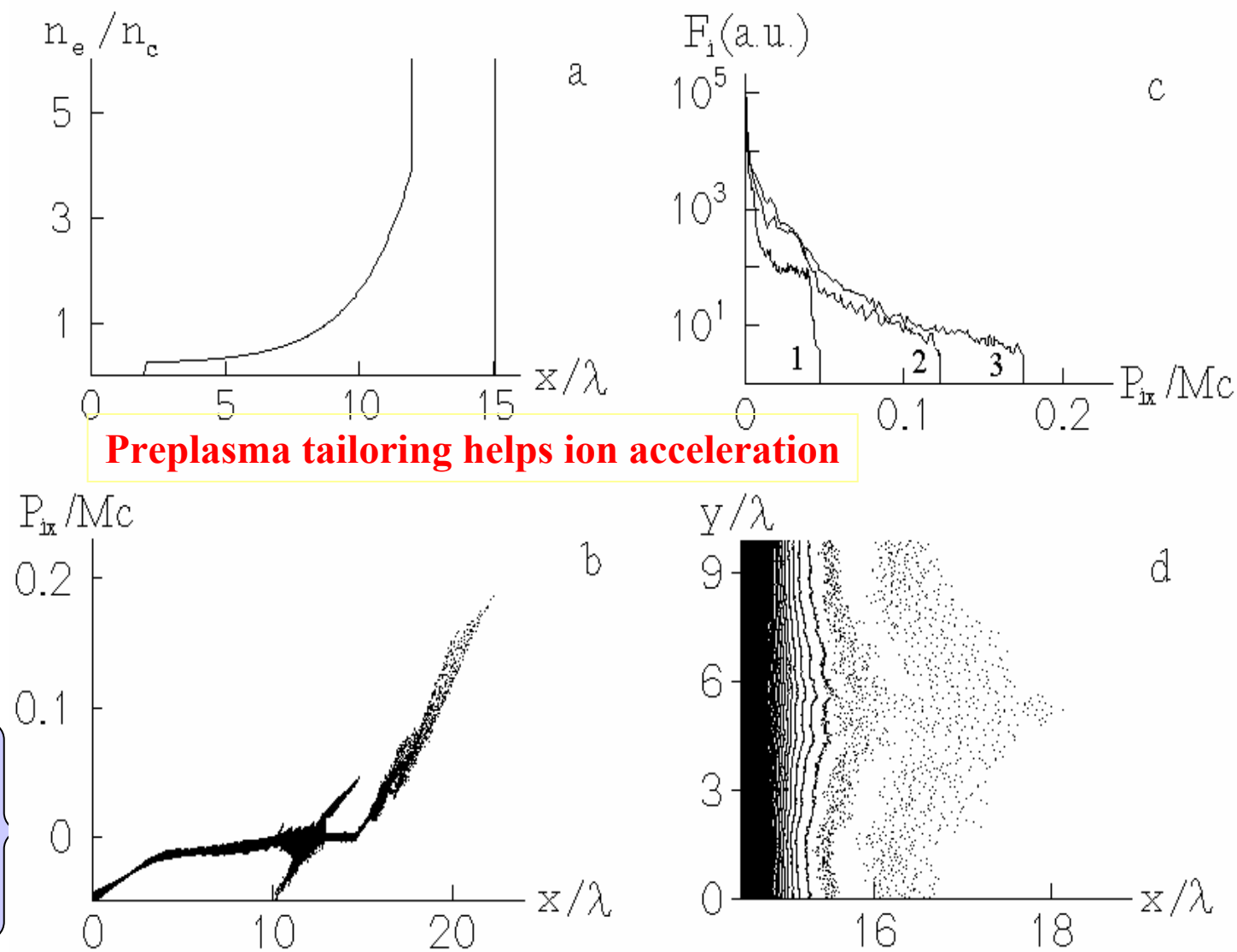
Ion acceleration by short laser pulse

$\tau_i \sim \sqrt{M/e^2 n_h}$

$n_h \sim n_c$

$\Downarrow$

$\tau_i \sim 100 fs$



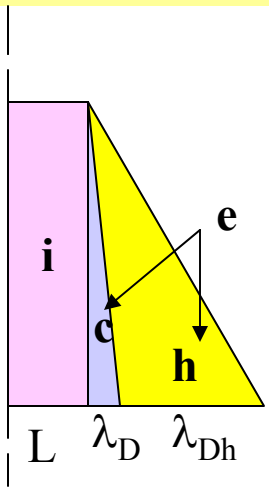
Preplasma tailoring helps ion acceleration

a=7

l=12λ~L

$\varepsilon_{max} \cong 15$ MeV

Vlasov-Poisson model



$$\partial_t f_\alpha + \mathrm{v}\partial_x f_\alpha + (e_\alpha/m_\alpha)E\partial_\mathrm{v} f_\alpha = 0$$

$$n_{h,c} = n_{h0,c0}\exp(e\Phi/T_{h,c})$$

$$\partial_{xx}\Phi = 4\pi e[n_{h0}\exp(e\Phi/T_h) + n_{c0}\exp(e\Phi/T_c) - \sum_\alpha Z_\alpha n_\alpha]$$

$$p(x) = n_h(x)T_h/n_c(x)T_c$$

$$x = L + \frac{\lambda_D}{\sqrt{2}}\int_{e\Phi/T_c}^{e\Phi(L)/T_c} du\left[e^u - 1 + p(0)\left(e^{T_c u/T_h} - 1\right) - \sum_\alpha \frac{Z_\alpha n_\alpha}{n_{c0}} u\right]^{-1/2}, \; x < L,$$

$$x = L - \frac{\lambda_D}{\sqrt{2}}\int_{e\Phi(L)/T_c}^{e\Phi/T_c} du\left[e^u + p(0)\,e^{T_c u/T_h}\right]^{-1/2}, \quad x > L,$$

$$E(L) = E_0(L)\sqrt{\exp[-p(0)] + \mathrm{e}p(0)}$$

$$E_0(L) = \sqrt{2/\mathrm{e}}\,(4\pi n_{c0}T_c)^{1/2} = 0.94(4\pi n_{c0}T_c)^{1/2}$$

$$E(L) = \sqrt{8\pi n_{h0}T_h} \Rightarrow p(0) \gg 1$$

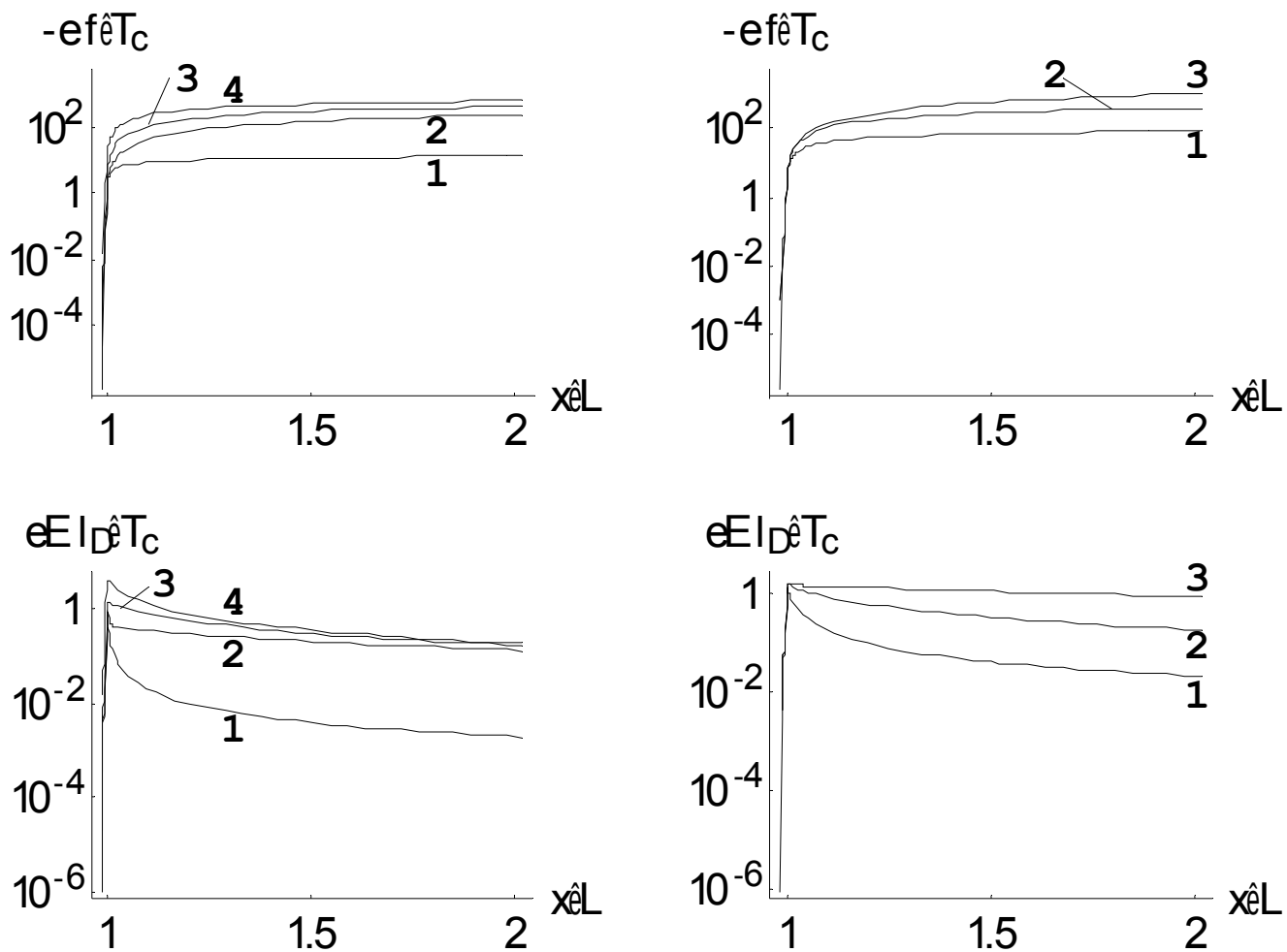
$$\Delta \equiv \frac{x-L}{\lambda_D} = \sqrt{\frac{2}{p}}\exp\left(-\frac{e\Phi}{2T_h}\right)\mathrm{Arcsinh}\sqrt{p} - \sqrt{\frac{2}{p(L)}}\exp\left(-\frac{e\Phi(L)}{2T_h}\right)\mathrm{Arcsinh}\sqrt{p(L)}.$$

$$\Phi \approx -\frac{2T_h}{e}\ln\left[\frac{T_c\sqrt{p(0)}\Delta}{T_h\ln(\sqrt{p(0)}\Delta)}\right],$$

Initial field distribution

Ion acceleration depends on cold electron heating (due to current neutralization). Cold electron pressure boost increases the amplitude of the electric field.

Spatial distributions of the electrostatic potential (top panels) and electric field (bottom panels) for $L/\lambda_D=1000$, $n_{h0} << n_{c0}$, and $\Sigma_\alpha Z_\alpha n_\alpha = n_{c0}+n_{h0}$. The left panels correspond to T_c/T_h=0.01 and $n_{h0}T_h/n_{c0}T_c=0$ (1), 0.1 (2), 1 (3), and 10 (4). The right panels correspond to $n_{h0}T_h/n_{c0}T_c= 1$ and $T_c/T_h=0.1$ (1), 0.01 (2), and 0.001 (3)



Light and heavy ion acceleration

Multi-species plasma with cold and hot electrons

Z_1=4, Z_2=1, A_1=12, A_2=1, n_{h0}/n_{c0}=0.01, $n_{10}=n_{20}$ 0.2n_{c0}, T_h/T_c=1000, $T_{10,20}/T_c$=0.1

A presence of even small number of hot electrons provides effective acceleration of small population of ions, both light and heavy, p(0) ¨ 1

Scales: $x \Rightarrow \lambda_{Dh}$ $\quad \mathrm{v} \Rightarrow c_0 = \sqrt{T_h/M_p}$ $\quad t \Rightarrow t_0 = \lambda_{Dh}/c_0$

$$a = T_h/T_c >> 1 \qquad b = n_{h0}/n_{c0} << 1$$

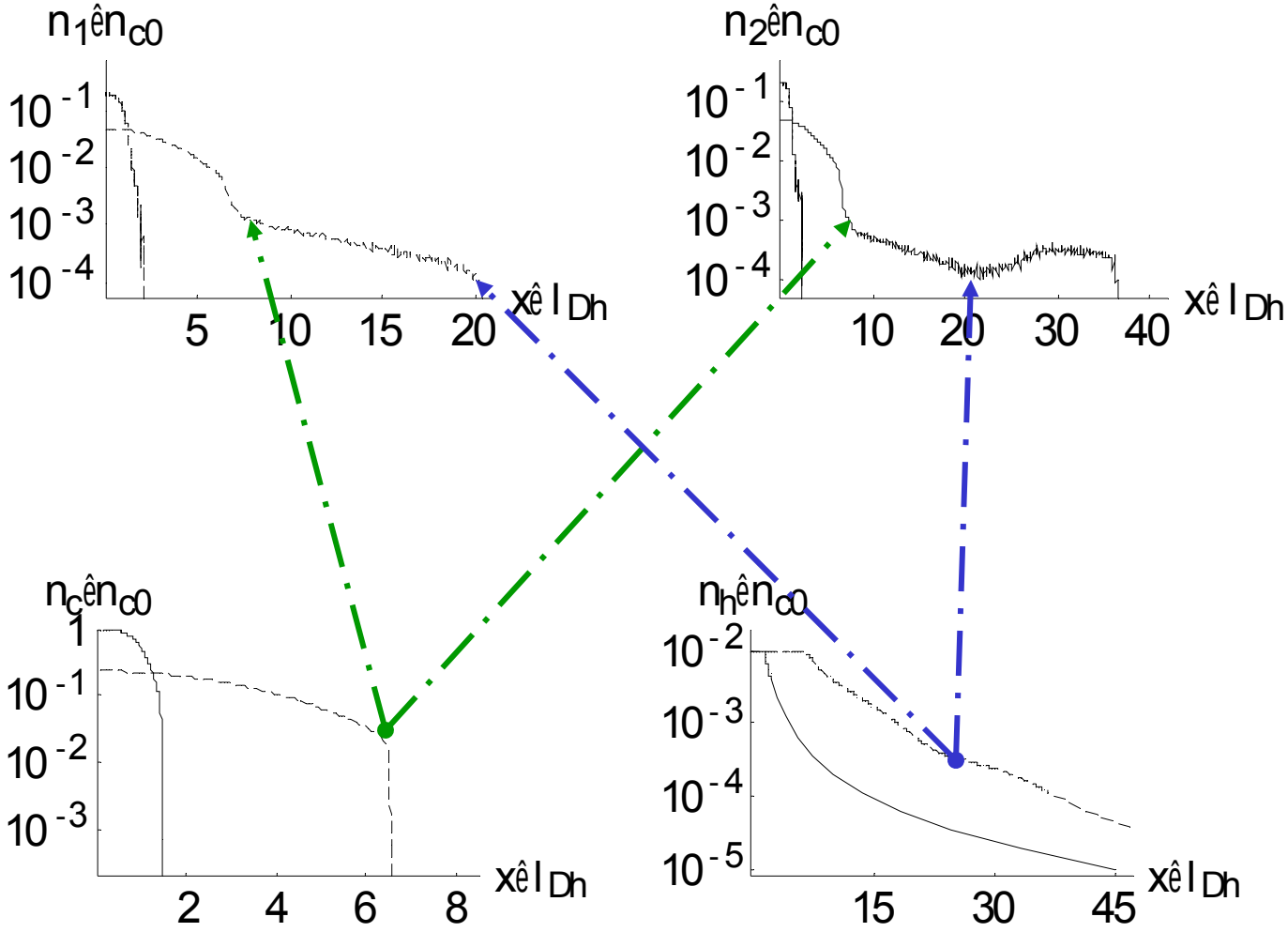
$$\partial_t f_\alpha + \mathrm{v}\partial_x f_\alpha + (Z_\alpha/A_\alpha)\Phi'\partial_{\mathrm{v}} f_\alpha = 0, \quad f_\alpha(\mathrm{v}, t=0) = F_{\alpha M}(\mathrm{v})$$

PIC method ↵

$$b\Phi'' = be^{\Phi} + e^{a\Phi} - \sum_\alpha Z_\alpha n_\alpha, \ \Phi'(0,t) = 0, \ \frac{\Phi'(x_b,t)}{\sqrt{2}} = -\sqrt{\frac{e^{a\Phi}}{ab} + e^{\Phi}}$$

Newton-Kantorovitch algorithm ↵

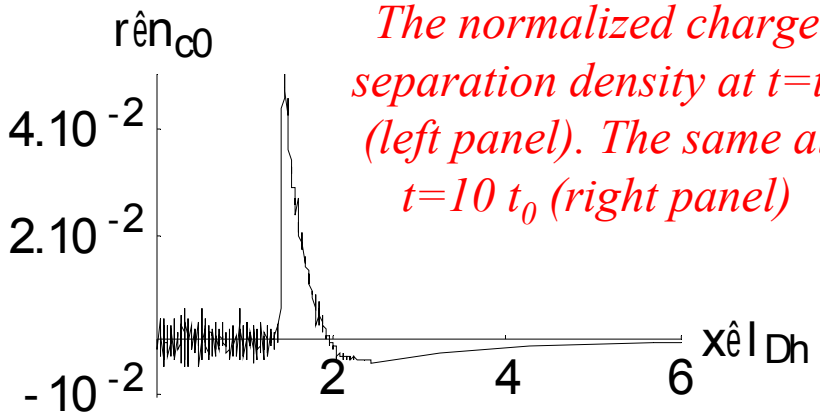
Particle densities



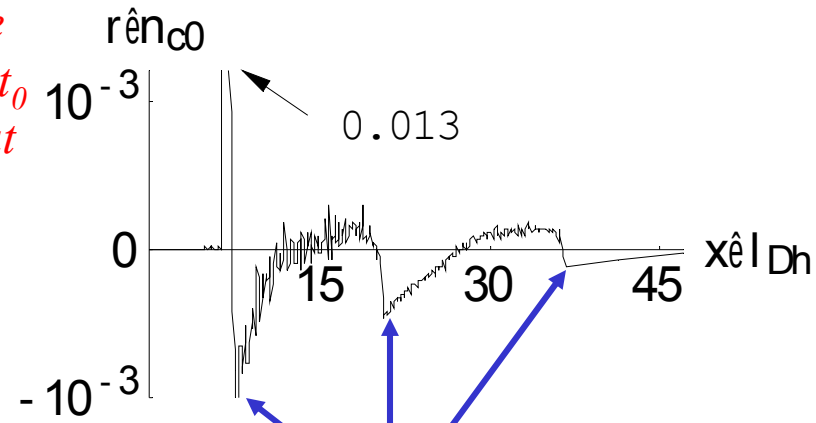
The normalized proton and carbon densities at $t = t_0$ (solid lines) and $t = 10\ t_0$ (dashed lines)

The cold electron and hot electron densities at $t=t_0$ (solid lines) and $t = 10\ t_0$ (dashed lines)

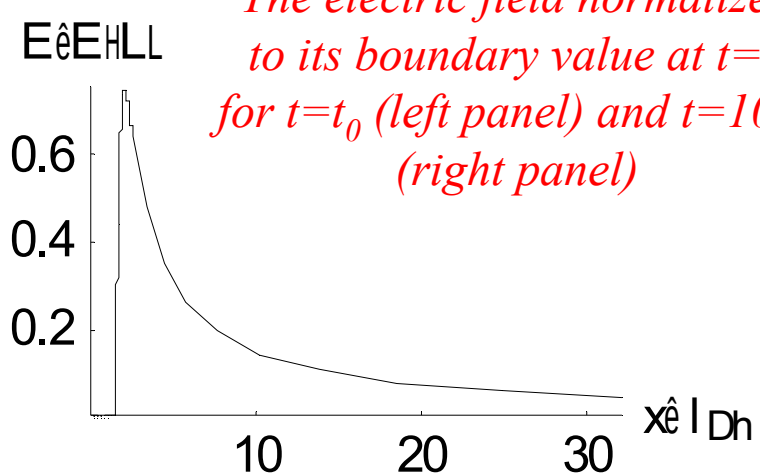
Charge separation field



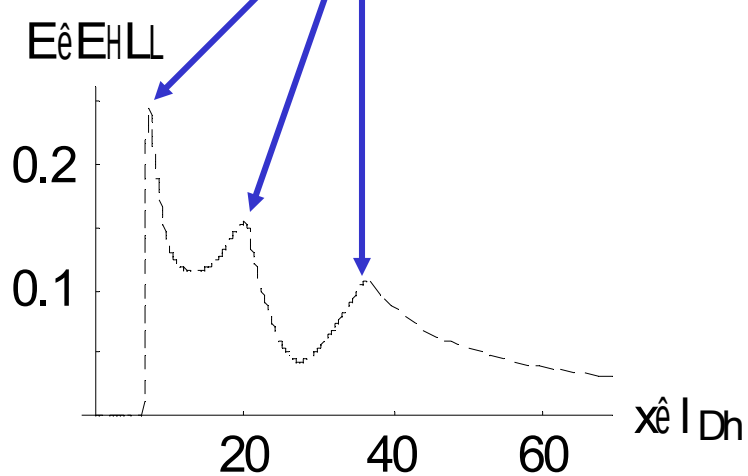
The normalized charge separation density at $t=t_0$ (left panel). The same at $t=10\ t_0$ (right panel)



Three ion fronts: of fast protons, fast carbon ions, and the bulk ions



The electric field normalized to its boundary value at $t=0$ for $t=t_0$ (left panel) and $t=10\ t_0$ (right panel)



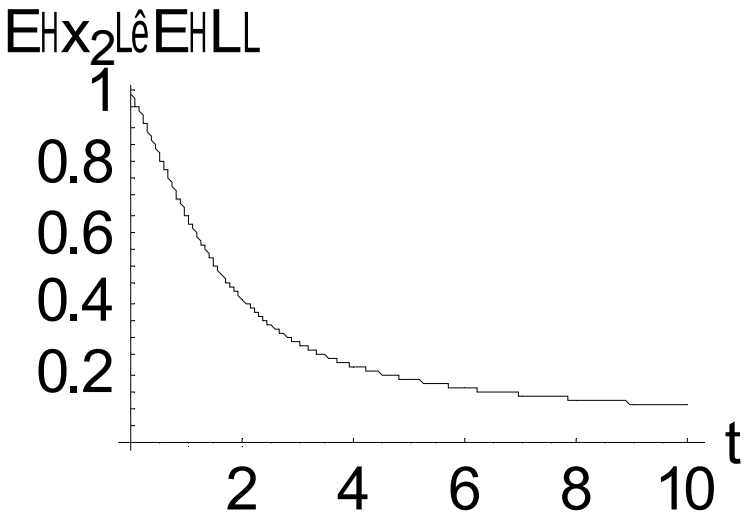
Ion front propagation

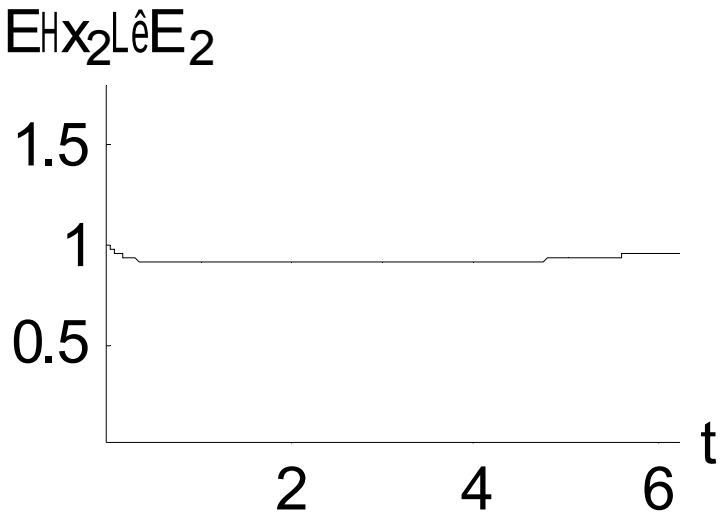
$$E_2 = \frac{E(L)}{\sqrt{1+(t/t_0)^2}}$$

$$m_2 d\mathrm{v}_2/dt = Z_2 e E_2$$

$$\Downarrow$$

$$\mathrm{v}_2 = \sqrt{2}\, c_2 \ln(t/t_0 + \sqrt{t^2/t_0^2 + 1})$$





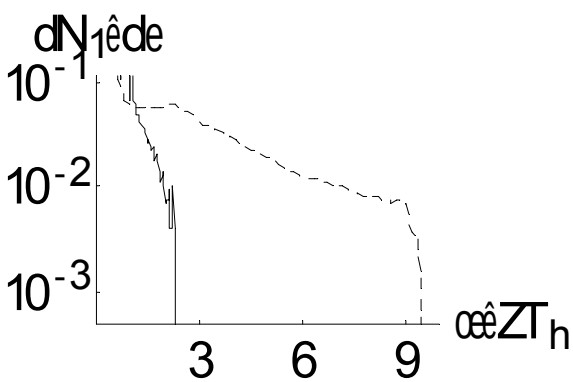
The time dependence of the electric field $E(x_2)$ at the proton front (left panel) and comparison of this electric field with the fitting expression E_2 (right panel)

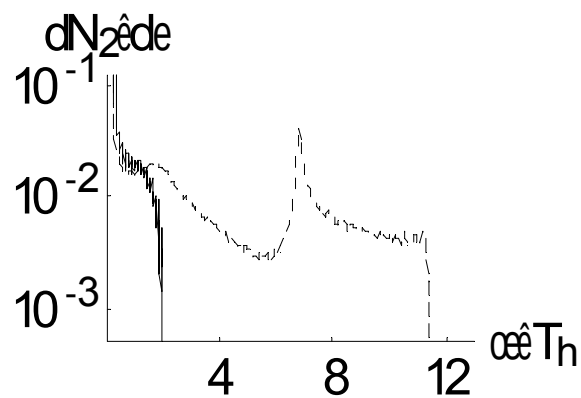
Energy spectra of accelerated ions

p **µ** $\varepsilon_{2,max} = T_h(\ln t/t_0)^2$ t ¨ t_0

C **µ** $\varepsilon_{1,max} = ZT_h(\ln[\sqrt{Z}t/\sqrt{A}t_0])^2$

$$\frac{\varepsilon_{1,max}}{\varepsilon_{2,max}} \approx Z\left(1 - \frac{\ln[A/Z]}{2\ln[t/t_0]}\right)^2$$



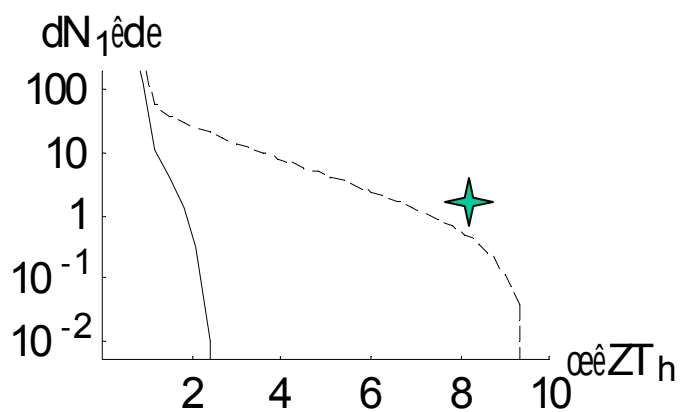


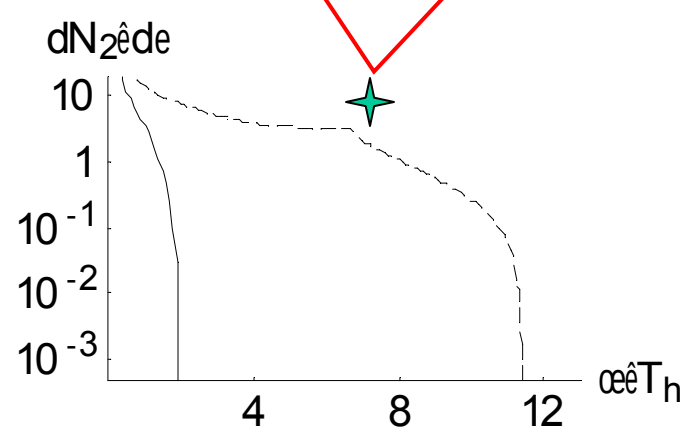
Heavy ion influence through E

ε - in T_h units

t_0

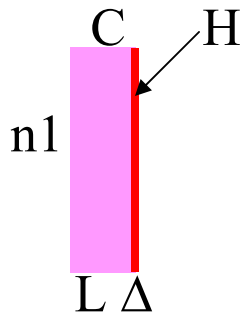
$10\ t_0$





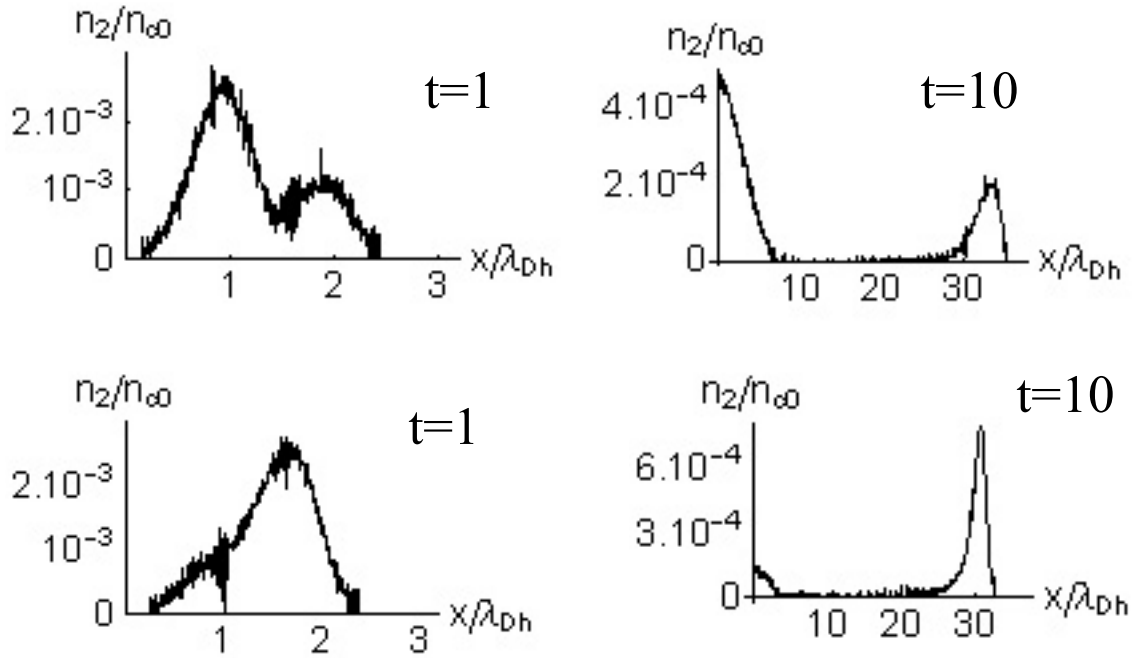
L= λ_{Dh} µ 0.1 λ_{Dh} µ 4% decrease in ε_{max}

Ion acceleration from double layer target (contamination layer)



Z_1=4, Z_2=1, A_1=12, A_2=1, n_{h0}/n_{c0}=0.01, $n_{10}=n_{20}$, T_h/T_c=1000, $T_{10,20}/T_c$=0.1

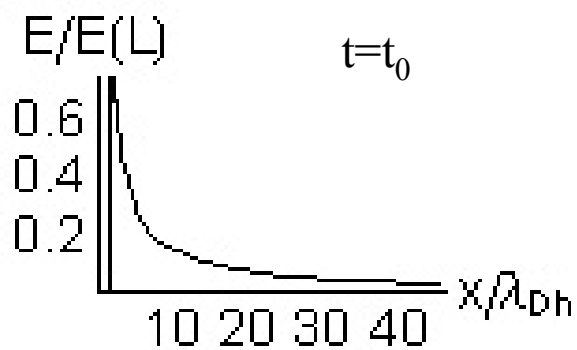
High-energy proton bunch formation*) Δ=0.01L

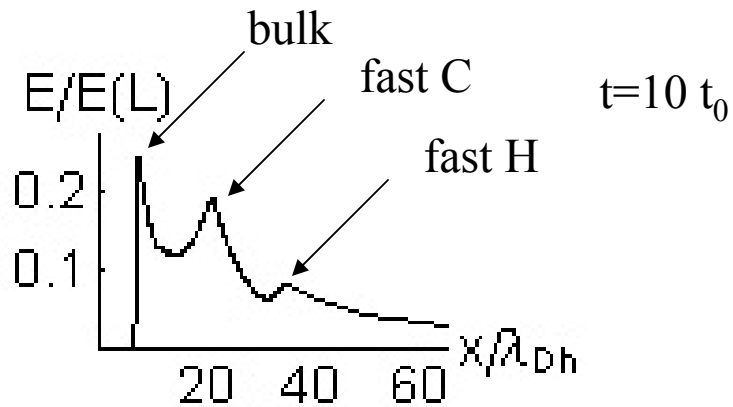


n_{h0}/n_{c0}=0.1 →

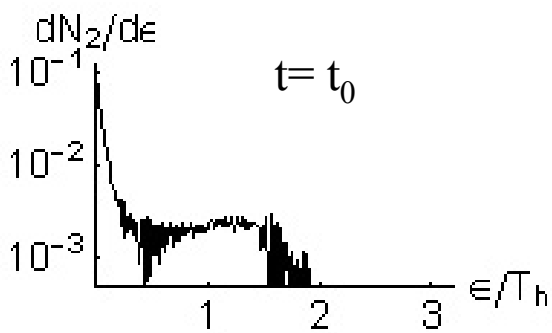
) T. Zh. Esirkepov, S. V. Bulanov, K. Nishihara, et al., Phys. Rev. Lett.* ***89**, 175003 (2002)*

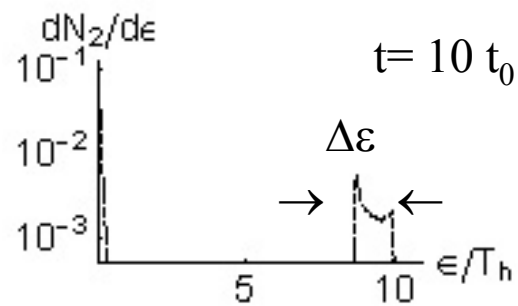
Characterization of accelerated protons





Energy spectra of protons





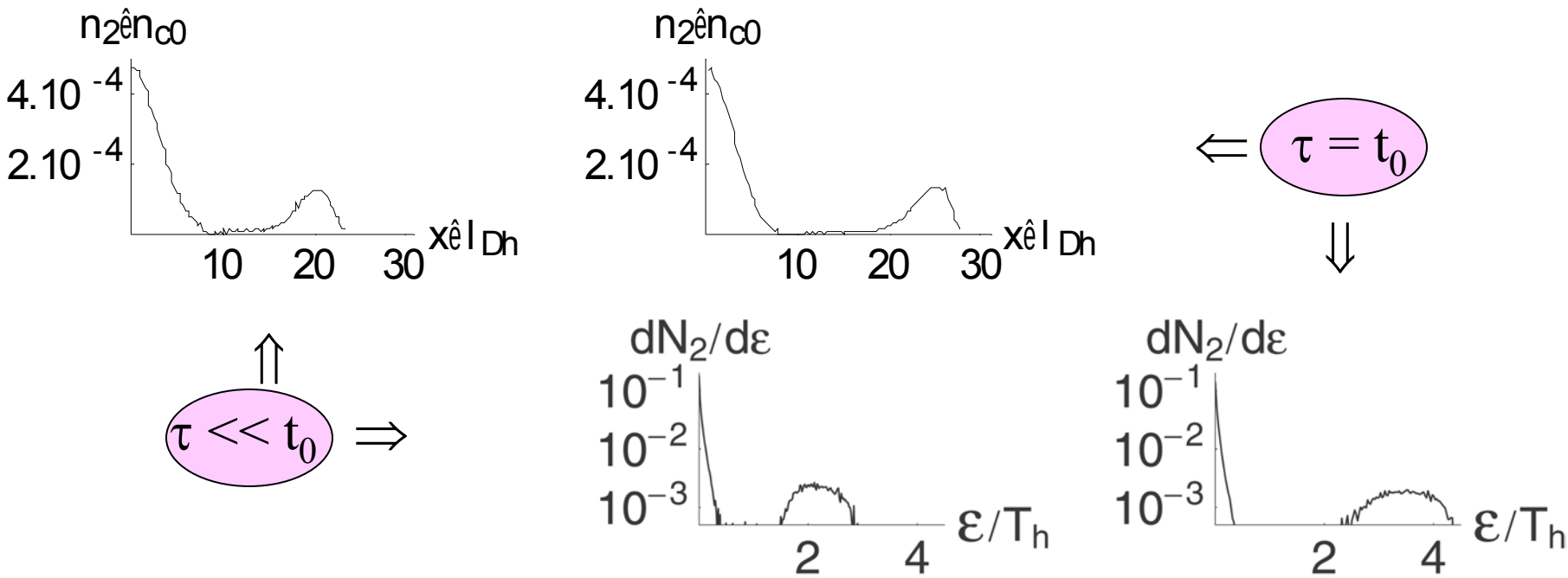
$$\Delta\varepsilon(t) \approx T_h = \text{const}$$

Ion acceleration with cooling electrons

$T_h \equiv T_h(t) \rightarrow$ Adiabatic cooling (1), temporal shape of the laser pulse (2)

(1)

$$T_h(t) = T_h, \text{ if } t \le \tau, \quad T_h(t) = \frac{T_h}{1+(t-\tau)^2/t_0^2}, \text{ if } t > \tau.$$



(2) Proton energy spectrum can be considerably narrowed by proper chose of the laser pulse shape [$I_{max} \sim I(t=t_0)$]

Analytical theory of plasma expansion

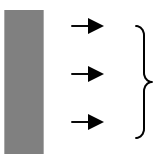
Using the renormalization group symmetry (RGS) method *) makes it now possible to apply it to ion acceleration.

Solution to the Cauchy problem for the kinetic equations with quasi-neutrality conditions

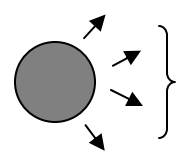
$$\partial_t f^\alpha + \mathrm{v}\partial_x f^\alpha - (e_\alpha/m_\alpha)(\partial_x \Phi)\partial_\mathrm{v} f^\alpha = 0$$

$$f^\alpha|_{t=0} = f_0^\alpha(x,v)$$

$$\int \mathrm{dv} \sum_\alpha e_\alpha f^\alpha = 0, \quad \int \mathrm{dv}\, \mathrm{v} \sum_\alpha e_\alpha f^\alpha = 0, \quad \partial_x \Phi = -\int \mathrm{dv} \sum_\alpha e_\alpha \mathrm{v}^2 \partial_x f^\alpha \left\{\int \mathrm{dv} \sum_\alpha \frac{e_\alpha^2}{m_\alpha} f^\alpha\right\}^{-1}.$$



*V. F. Kovalev, V. Yu. Bychenkov, and V. T. Tikhonchuk, JETP **95**, 226 (2002)*



*V. F. Kovalev and V. Yu. Bychenkov, Phys. Rev. Lett. **90**, 185004 (2003)*

Advantages:

- Analytics. Parametric dependencies;
- Multi-species plasma;
- Adiabatic cooling;
- Both geometries: plane, spherical.

Disadvantages:

- Quasineutrality;
- Nonrelativism;
- After pulse acceleration.

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*) *V. F. Kovalev, V. V. Pustovalov, and D. V. Shirkov, J. Math.Phys. **39**, 1170 (1998).*

RGS method

The key idea is to find the RGS providing an invariance of the solution to the initial value problem for t → 0: $f^{\alpha} = F^{\alpha}(t,x,v) \equiv f_0^{\alpha}(x,v) + O(t)$ and to formulate the finite transformations which extend this solution to the solution for t > 0.

$$X_{\alpha} = Z_{\alpha+1}^{-1}\partial_{f^{\alpha+1}} - Z_{\alpha}^{-1}\partial_{f^{\alpha}};\ X_0 = \partial_t;\ X_1 = \partial_x;$$
$$X_2 = t\partial_t - \mathrm{v}\partial_{\mathrm{v}};\ X_3 = x\partial_x + \mathrm{v}\partial_{\mathrm{v}};\ X_4 = \sum_{\alpha} f^{\alpha}\partial_{f^{\alpha}};$$
$$X_5 = t\partial_x + \partial_{\mathrm{v}};\ X_6 = t^2\partial_t + tx\partial_x + (x - \mathrm{v}t)\partial_{\mathrm{v}};$$

RGS generator appears as a linear combination of generators X_0 and X_6

RGS transformation of the phase space (x'v') at t=0 to (x,v) for t>0.

group transformation

$$x' = \frac{x}{\sqrt{1+\Omega^2 t^2}}, \quad \mathrm{v}'^2 + \Omega^2 x'^2 = \mathrm{v}^2 + \Omega^2 (x - vt)^2$$

$$\Omega^{-1} = L_0/c_s$$

Invariants of the group transformation

$$f^{\alpha} = f_0^{\alpha}(I^{(\alpha)}),\ I^{(\alpha)} = \frac{1}{2}\left(\mathrm{v}'^2 + \Omega^2 x'^2\right) + \frac{e_{\alpha}}{m_{\alpha}}\Phi_0(x')$$

$$\Phi(t,x) = \Phi_0(x')\left(1 + \Omega^2 t^2\right)^{-1}$$

Solution to the initial value problem

CH plasma with cold and hot electrons

$$f^e = \frac{n_{c0}}{\sqrt{2\pi}\mathrm{v}_{Tc}} \exp\left(-I^{(c)}/v_{Tc}^2\right) + \frac{n_{h0}}{\sqrt{2\pi}\mathrm{v}_{Th}} \exp\left(-I^{(h)}/\mathrm{v}_{Th}^2\right), \quad \mathrm{v}_{T\alpha}^2 = \frac{T_\alpha}{m_\alpha},$$

$$f^1 = \frac{n_{10}}{\sqrt{2\pi}\mathrm{v}_{T1}} \exp\left(-I^{(1)}/v_{T1}^2\right), \quad f^2 = \frac{n_{20}}{\sqrt{2\pi}\mathrm{v}_{T2}} \exp\left(-I^{(2)}/\mathrm{v}_{T2}^2\right),$$

$$u = xt\Omega^2/(1+\Omega^2 t^2)$$

$$U = x\Omega/\sqrt{1+\Omega^2 t^2}$$

$$\frac{I^{(c)}}{\mathrm{v}_{Tc}^2} = E + \frac{(1+\Omega^2 t^2)}{2\mathrm{v}_{Tc}^2}(\mathrm{v}-u)^2, \quad \frac{I^{(h)}}{\mathrm{v}_{T_h}^2} = E\frac{T_c}{T_h} + \frac{(1+\Omega^2 t^2)}{2\mathrm{v}_{Th}^2}(\mathrm{v}-u)^2,$$

$$\frac{I^{(1)}}{\mathrm{v}_{T1}^2} = -E\frac{Z_1 T_{c0}}{T_{10}} + \frac{U^2}{2\mathrm{v}_{T_1}^2}\left(1+\frac{Z_1 m_e}{m_1}\right) + \frac{(1+\Omega^2 t^2)}{2\mathrm{v}_{T_1}^2}(\mathrm{v}-u)^2,$$

$$\frac{I^{(2)}}{\mathrm{v}_{T2}^2} = -E\frac{Z_1 T_{c0}}{T_{10}} + \frac{U^2}{2\mathrm{v}_{T_2}^2}\left(1+\frac{Z_2 m_e}{m_2}\right) + \frac{(1+\Omega^2 t^2)}{2\mathrm{v}_{T_2}^2}(\mathrm{v}-u)^2.$$

$$E = \frac{e\Phi}{T_c}(1+\Omega^2 t^2) + \frac{U^2}{2\mathrm{v}_{Tc}^2}$$

obeys the transcendental equation

$$1+\sigma-\rho_h = \exp\left[\left(1+\frac{Z_1 T_c}{T_1}\right)E - \frac{U^2}{2\mathrm{v}_{T1}^2}\left(1+\frac{Z_1 m_e}{m_1}\right)\right] - \rho_h \exp\left[\left(1-\frac{T_c}{T_h}\right)E\right]$$

$$+\sigma \exp\left[\left(1+\frac{Z_2 T_c}{T_2}\right)E - \frac{U^2}{2\mathrm{v}_{T2}^2}\left(1+\frac{Z_2 m_e}{m_2}\right)\right], \quad \rho_h = \frac{n_{h0}}{Z_1 n_{10}}, \quad \sigma = \frac{Z_2 n_{20}}{Z_1 n_{10}}.$$

Integral characteristics

$$n_q = \int_{-\infty}^{\infty} \mathrm{d}\mathrm{v} f^q, \quad \frac{dN_q}{d\varepsilon} = \frac{1}{m_q \mathrm{v}} \int_{-\infty}^{\infty} \mathrm{d}x \left(f^q(t,x,\mathrm{v}) + f^q(t,x,-\mathrm{v}) \right).$$

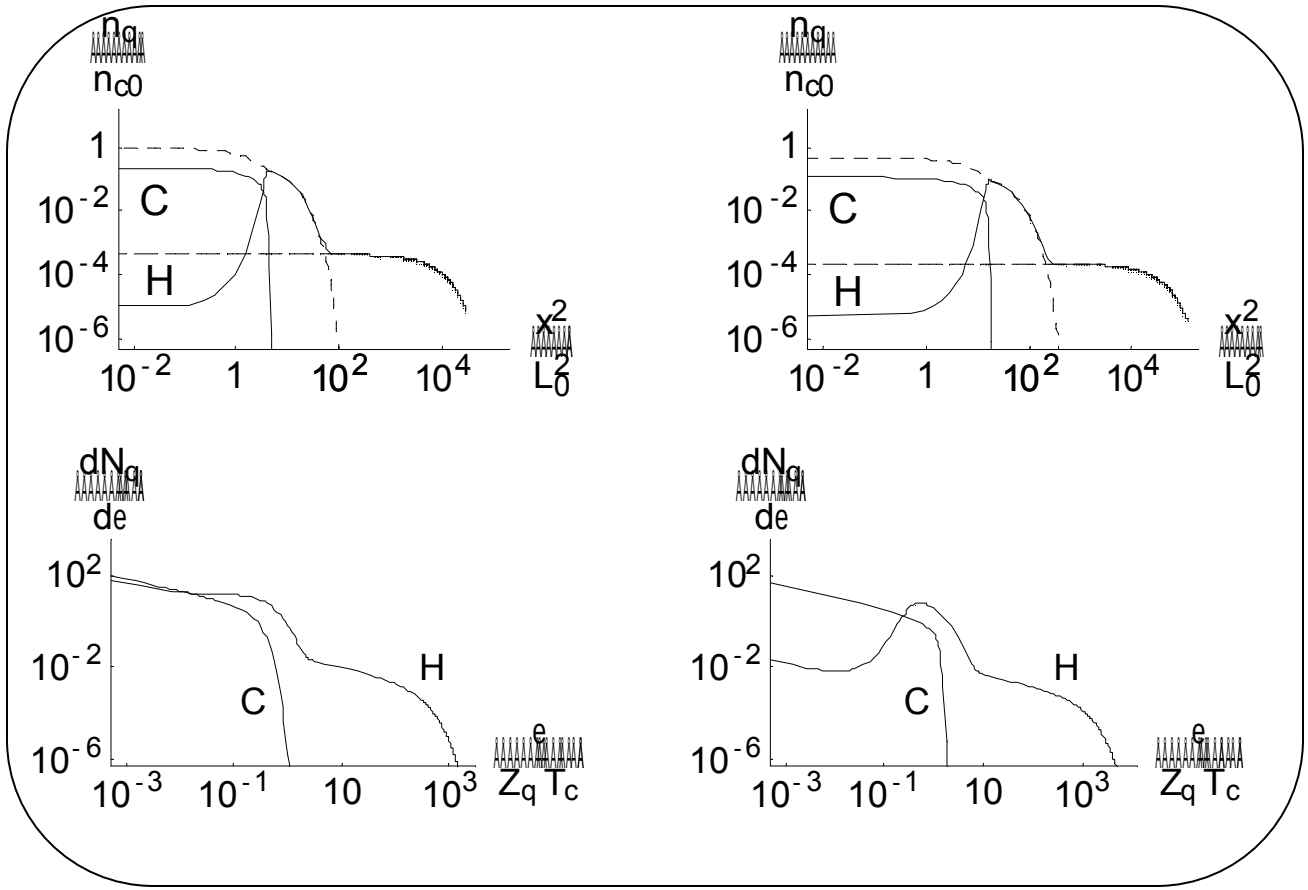
$$n_q = \frac{n_{q0}}{\sqrt{1+\Omega^2 t^2}} N_q(U), \quad N_q(U) = \exp\left(\frac{Z_q T_c}{T_q} E - \frac{U^2(1+Z_q m_e/m_q)}{2\mathrm{v}_{Tq}^2} \right).$$

$$\frac{dN_q}{d\varepsilon} \approx \sqrt{\frac{2}{m_q \varepsilon}} \frac{n_{q0}}{\Omega} N_q\left(\varepsilon = \frac{m_q U^2}{2}\right)$$

The same parameters as
In Vlasov-Poisson model

adiabatic cooling
$\propto \exp(-\mathrm{v}^2)$

$\propto \exp(-\mathrm{v})$
isothermal electrons



Conclusions

- ***Three models (PIC, Vlasov-Poisson, and analytic RGS) are well suited for study of high-energy ion generation by short laser pulses in multi-species plasma;***
- ***They are mutually complementary;***
- ***Target design and surface contamination are the crucial issues;***
- ***Electrostatic acceleration of electrons in preplasma is dominant mechanism of electron acceleration in few-wavelength preplasma by several-cycle pulses;***
- ***The charge-separation and the adiabatic cooling of particle are studied in detail.***