



Particle acceleration and neutron production from sub-micro-sized targets irradiated by an ultrashort laser pulse

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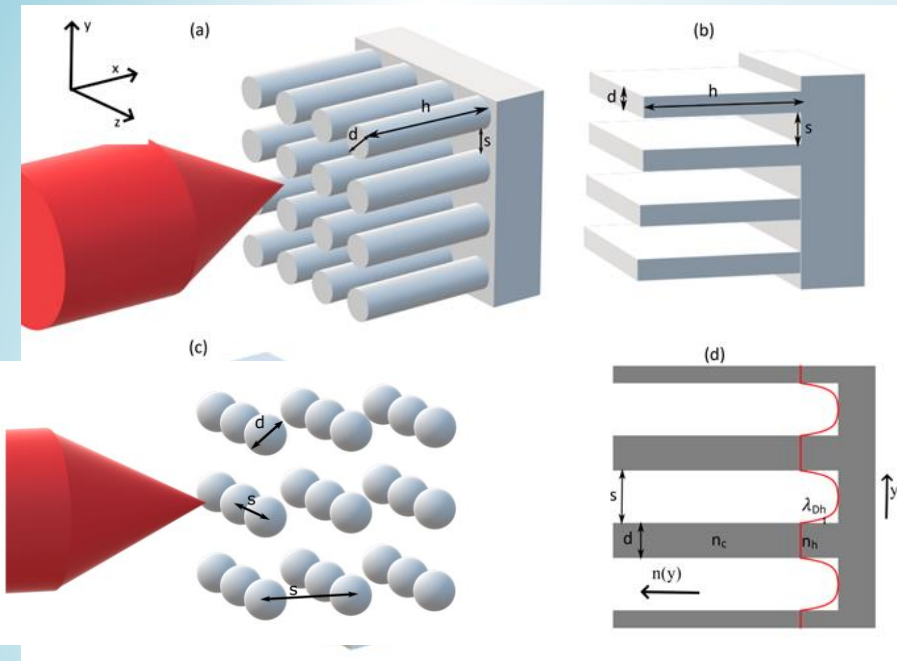
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**XXXVI International Conference on Interaction of Intense Energy Fluxes
with Matter (ELBRUS 2021), March 01-06, 2021**

Объемно нагреваемые микро-структурированные мишени



Прозрачность

Высокая средняя
плотность

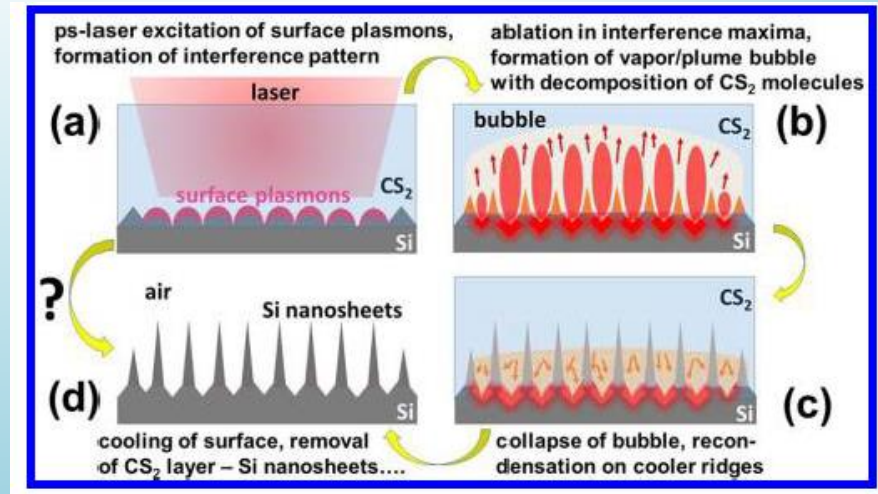
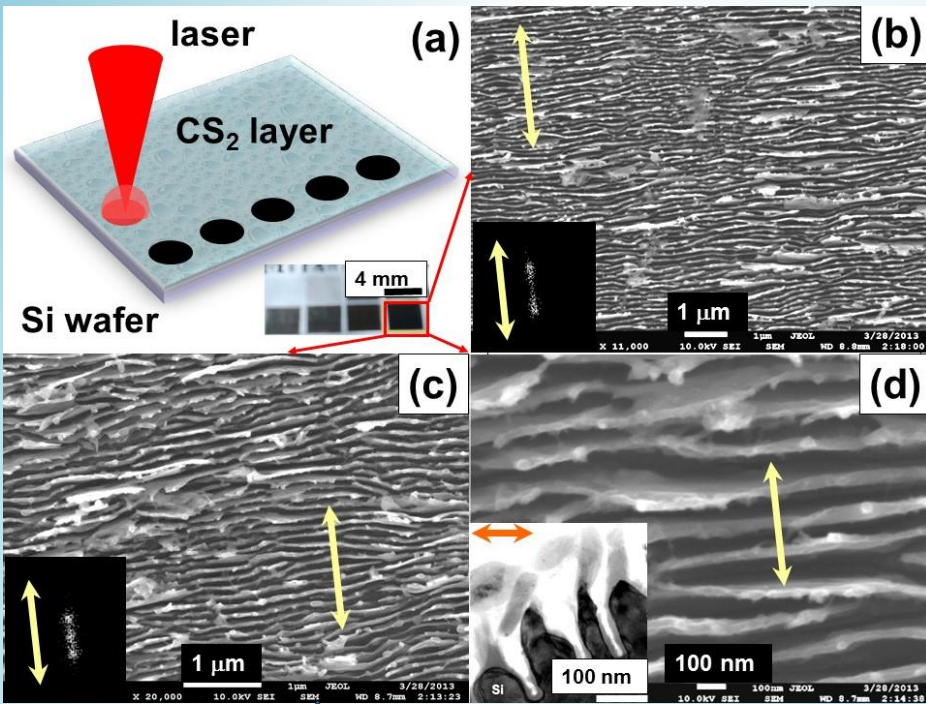
Эффективный объемный
нагрев (почти полное
поглощение лазерной
энергии)

Применения

☐ горячие электроны, рентген, ускоренные ионы, позитроны, ТГц, возможность использования компактных лазеров с энергией ~ 20 - 50 мДж, с частотой повторения 0.1 - 1 кГц

☐ ядерные реакции «на столе», high energy density research, пинчи

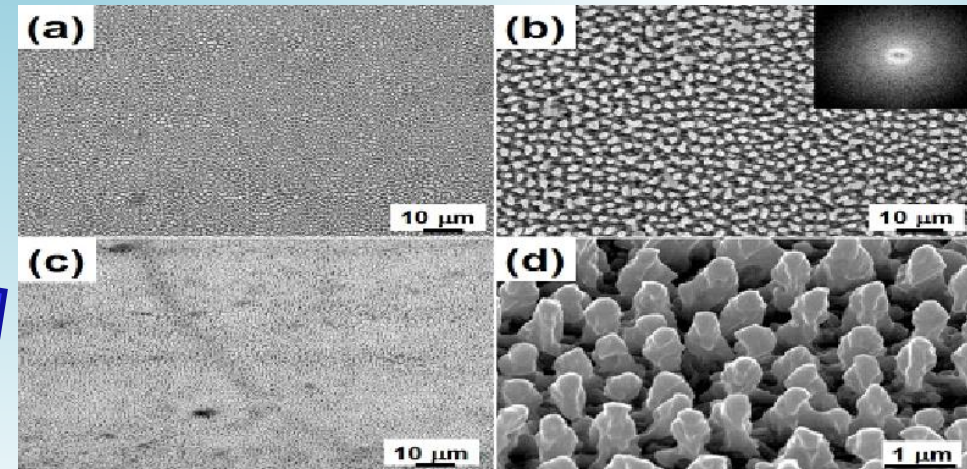
Laser Fabrication of Nano Sheet (Wire) Arrays



Nanoplasmonic Ablative Self-Organization

S.I. Kudryashov et al.,
ACS Appl. Nano Mater. 2461 (2018).

A.A. Ionin et al., Hydrodynamic instability and self-organization of a submicron relief on metal surfaces upon femtosecond laser exposure in liquids JETP Letters, 106 (2017)



PIC моделирование нагрева мишени

Setup	τ_L (fs)	$I_L(10^{18} \text{ W/cm}^2)$	focal spot (λ_L)	a_0	T_h^{PM} (keV)	\mathcal{E}_h^{EM} (keV)
I	30	1	4	0.85	85	185
II	60	2	2	1.2	160	370

$$T_h^{PM} = m_e c^2 \left(\sqrt{1 + a_0^2 / 2} - 1 \right)$$

$$\mathcal{E}_h^{EM} = m_e c^2 a_0^2 / 2$$

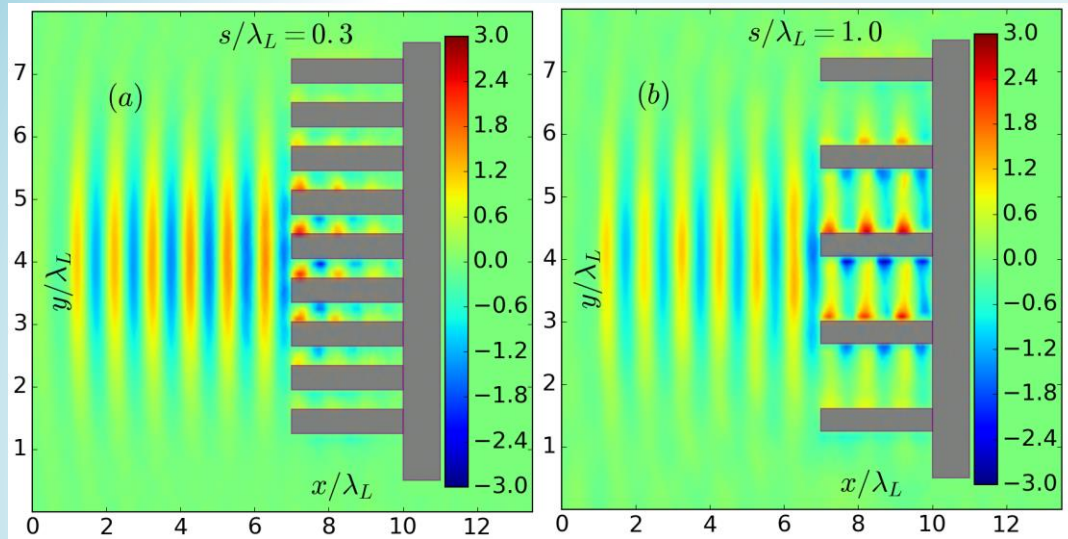
Mandor code : 3D3V PIC parallel simulations, 8 particles per cell, immobile ions

Box size: $7 \lambda_L \times 10 \lambda_L \times 10 \lambda_L, 0.005 \lambda_L, \times 0.02 \lambda_L, \times 0.02 \lambda_L,$

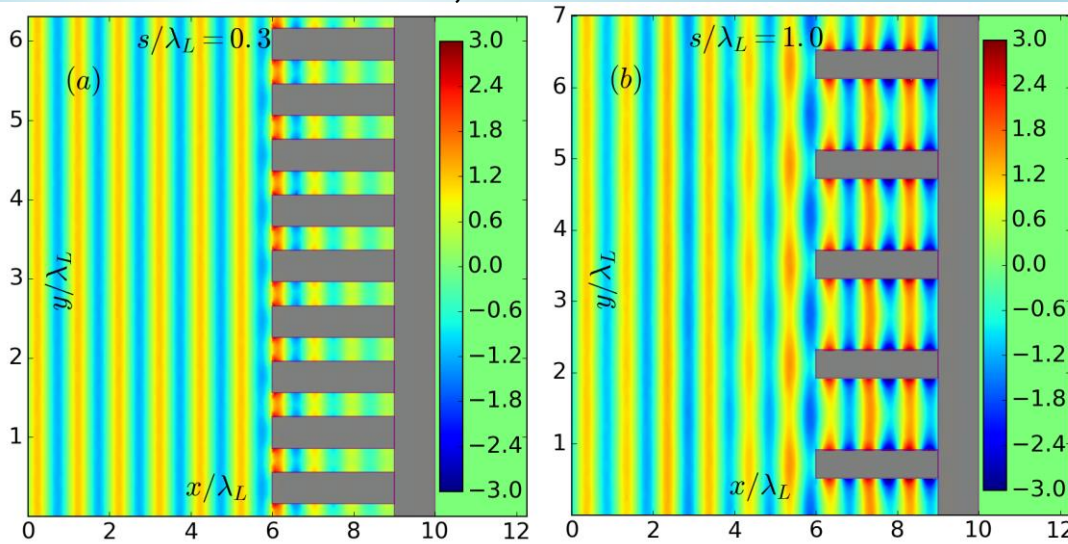
Linearly polarized laser pulse

Проникновение ЭМ поля в мишень

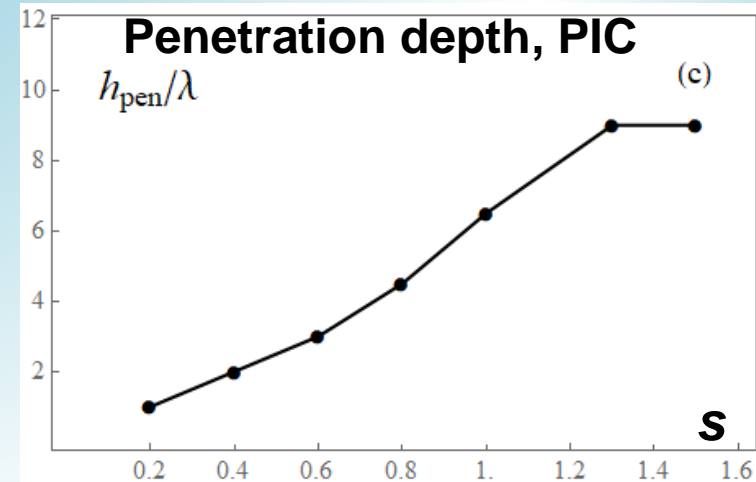
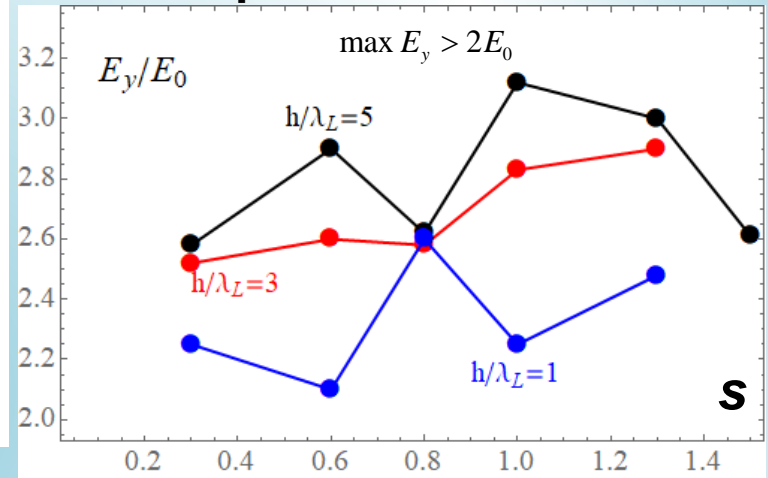
PIC, $I=2 \cdot 10^{18}$ W/cm², $D=2 \lambda_L$, $\tau=60$ fs, $\lambda_L=1 \mu\text{m}$ $h=1.5-7 \lambda_L$
 $d=0.4\lambda_L$



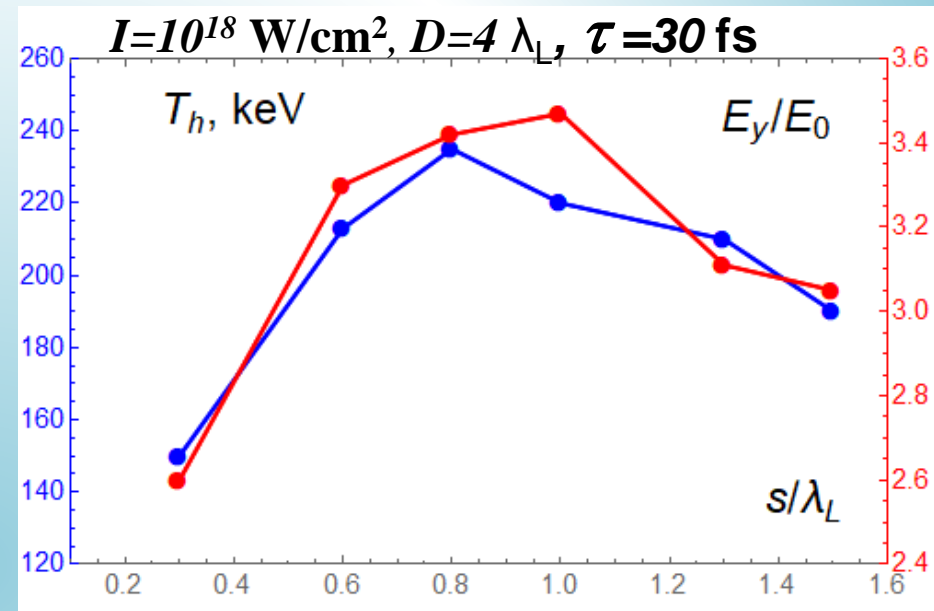
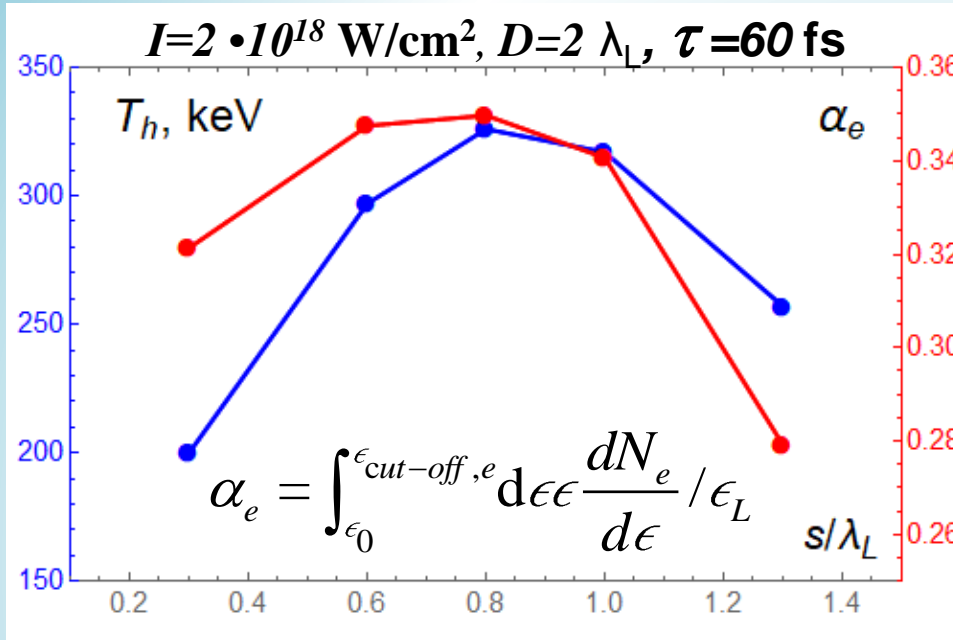
Maxwell solver, FIT



Amplitude of electric field



Оптимизация выхода горячих электронов



$$\epsilon_h^{\text{EM}} = m_e c^2 (\gamma_{\text{max}} - 1) = m_e c^2 a_0^2 / 2,$$

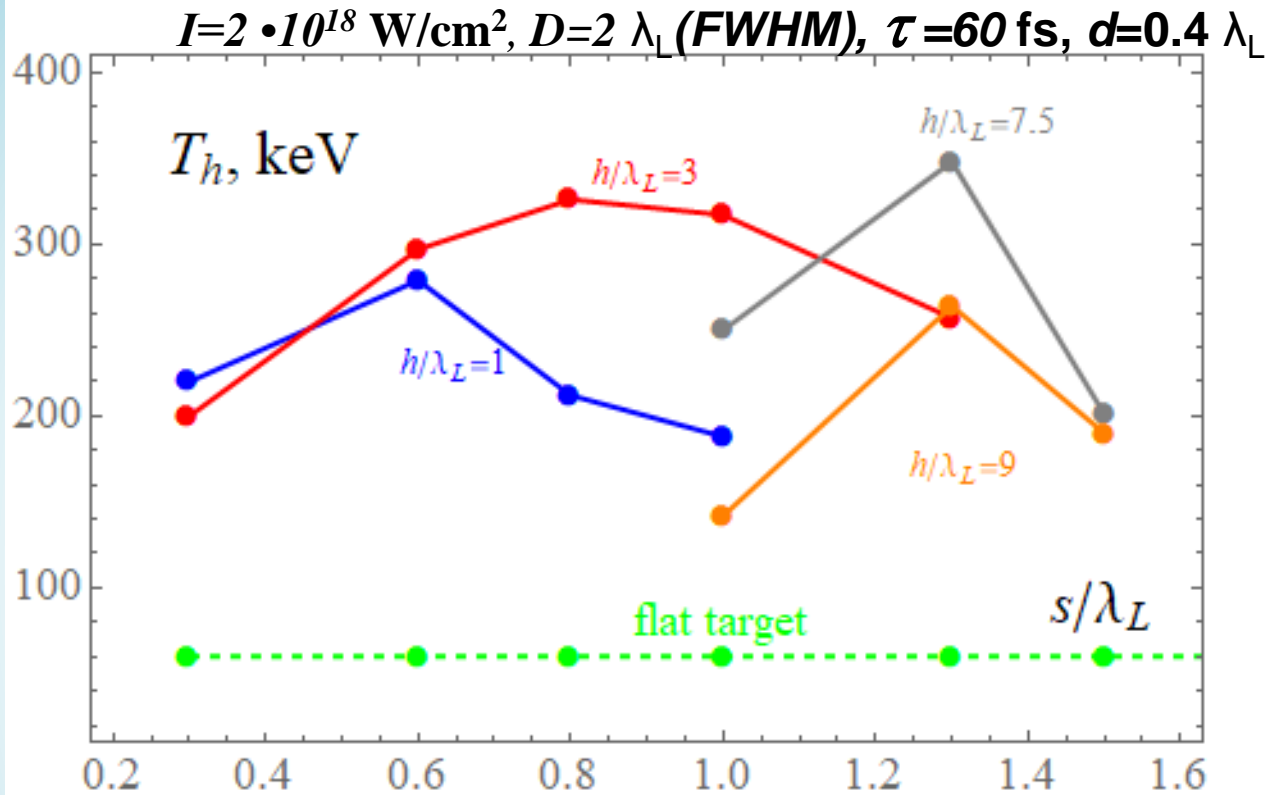
$$T_h^{\text{PM}} = \left((1 + a_0^2 / 2)^{1/2} - 1 \right) m_e c^2, \quad a_0 \approx 1 \Rightarrow \epsilon_h^{\text{EM}} \approx T_h^{\text{EM}}$$

Acceleration beyond the ponderomotive limit !!!

$$\epsilon_{\text{cut-off},e} \gg \epsilon_h^{\text{EM}} \approx 3 \text{ MeV},$$

$$T_h > T_h^{\text{EM}}$$

Оптимизация : температура горячих электронов



Absorption $\gtrsim 60\%$

flat surface $\approx 10\%$
 $T_h \approx 50 \text{ keV}$
 $(a_0 \approx 1.2)$

High average density

Optimal conditions for electron heating

$$s \gtrsim 2r_E \sim d, \quad h \sim h_{\text{pen}} \approx c\tau_L/2,$$

$$r_E = a_0\lambda_L/2\pi$$

presence of wave reflected favors stochastic heating

Механизмы ускорения электронов в объемно-нагреваемых мишенях



JxB, Brunel, vacuum heating/direct laser acceleration (DLA)



stochastic electron acceleration/heating

spectra of electrons from micro-wire targets:
two temperature



How to explain
generation of super –
ponderomotive
particles?

Laser pulse field +
arbitrary additional field
(e.m. field,
electrostatic field,
Coulomb, magnetic
field)

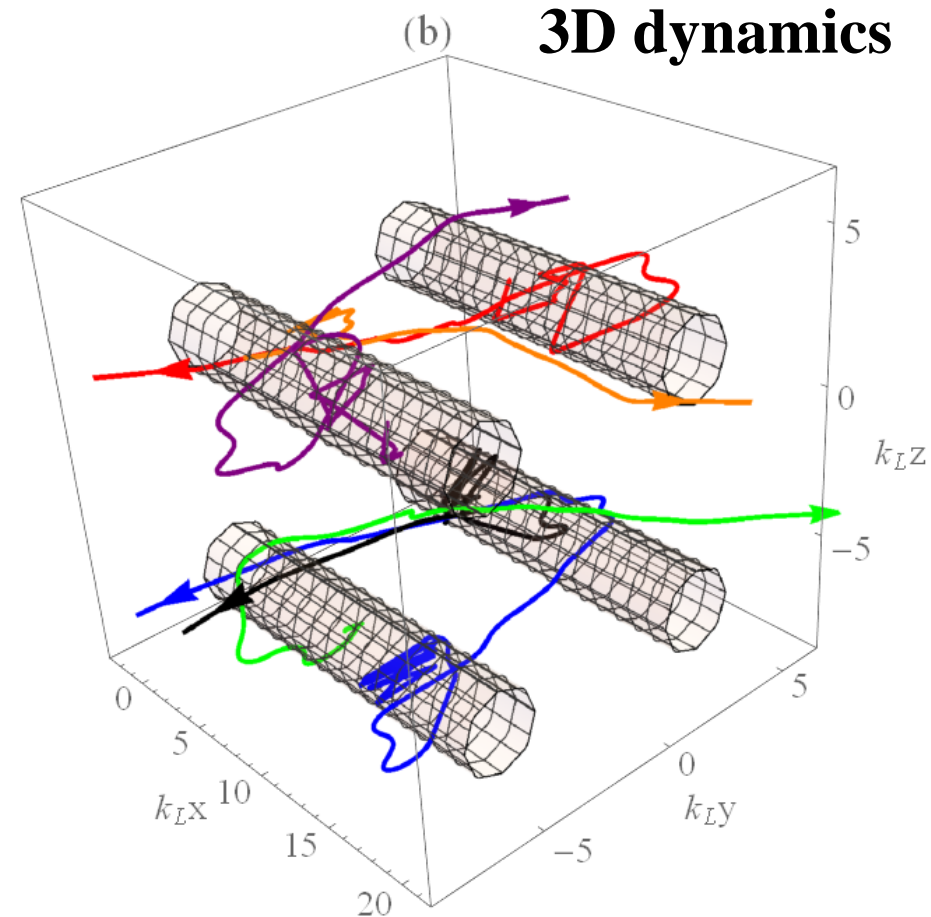
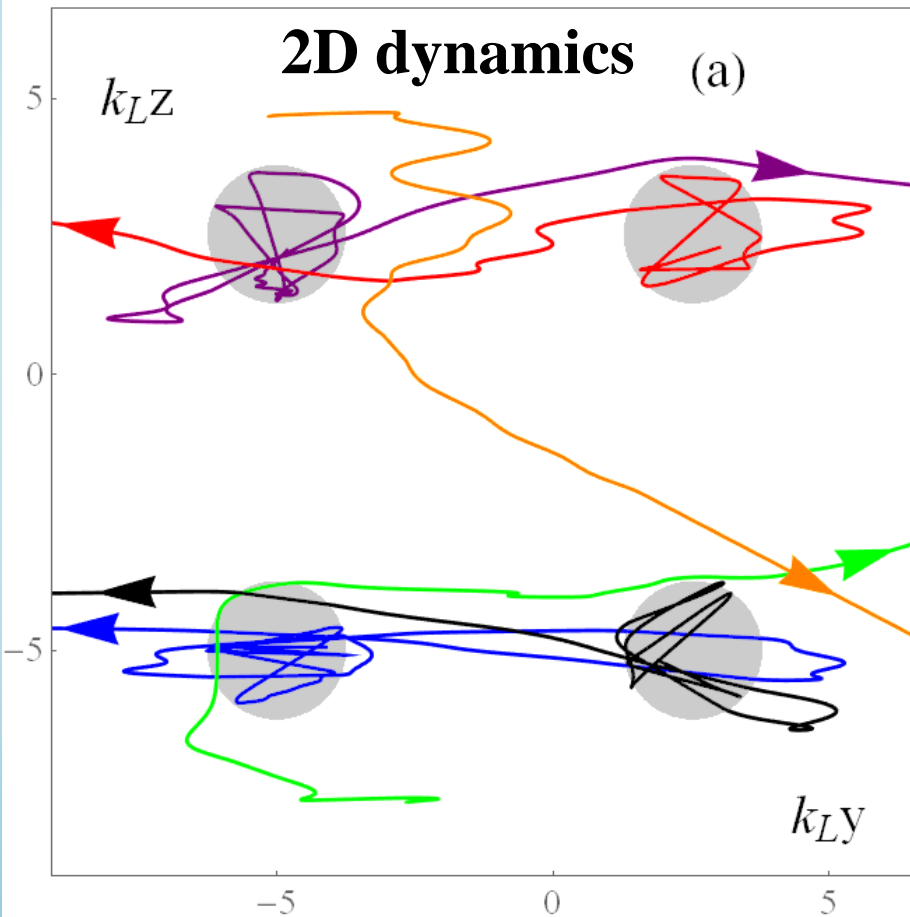
Динамика тестовых частиц в сложных полях

3D Test particle simulation

$$\frac{d}{dt} \vec{p} = -e\vec{E} - \frac{\vec{v}}{c} \times \vec{B}, \quad \frac{d}{dt} \vec{r} = \frac{\vec{p}}{m_e \gamma},$$

$$\vec{E} = \vec{E}_i + \vec{E}_r + \vec{E}_C$$

$$\vec{B} = \vec{B}_i + \vec{B}_r + \vec{B}_S$$



Описание квазистатических поле в микро структурах

$$E_y^i = E_0 f(r) \cos(\phi_-), \quad E_y^r = \hat{r} E_0 f(r) \cos(\phi_+ + \pi), \quad B_z^i = E_0 f(r) \cos(\phi_-), \quad B_z^r = \hat{r} E_0 f(r) \cos(\phi_+),$$

$$\phi_{\pm} = \omega_L t \pm k_L x + \phi_0, \quad f(r) = \sum_{n=1}^{N_{str}} \exp\left(-\frac{(d/2 - |\vec{R}_n|)}{l_s}\right).$$

$$\vec{E}^c(\vec{r}) = E_{Q0} \frac{m_e c \omega_L}{e} \sum_{n=1}^{N_{str}} \begin{cases} 0, \\ \left(1 - \frac{d}{2l_s} + \frac{|\vec{R}_n|}{l_s}\right) \frac{\vec{R}_n}{|\vec{R}_n|}, \\ \frac{C_Q \vec{R}_n}{|\vec{R}_n|^2} \exp\left(\frac{-|\vec{R}_n|}{r_d}\right), \end{cases}$$

$$\vec{R}_n = \vec{r}_{\perp} - \vec{r}_n, \quad C_Q = \frac{d}{2} \exp\left(\frac{d}{2r_d}\right),$$

$$\hat{r} \approx 0.7$$

$$E_{Q0}/E_0 \approx 0.7$$

$$B_{\phi 0}/E_0 \approx 0.6$$

$$j_{\parallel}(r = |\vec{R}_n|) = -ec n_{cr} B_{\phi 0} \begin{cases} 0, & r \leq d/2 - l_s \\ C_{j1} (r - d/2 + l_s)(r - d/2), & d/2 - l_s < r \leq d/2 \\ C_{j2} \exp\left(-\frac{r}{r_E}\right)(r - d/2), & r > d/2. \end{cases}$$

$$B_{\phi}^0(r_{\perp}) = \frac{4\pi}{cr_{\perp}} \int_0^{r_{\perp}} j_{\parallel}(r) r dr.$$

Метод показателей Ляпунова

Definition

$$\lambda_{\max} = \lim_{t \rightarrow \infty} \lim_{d(0) \rightarrow 0} \frac{1}{t} \ln \frac{d(\vec{x}_0, t)}{d(\vec{x}_0, 0)}, \quad d = |\vec{X}(\vec{x}_0, t) - \vec{X}(\vec{x}_0 + \delta \vec{x}_0, t)|.$$

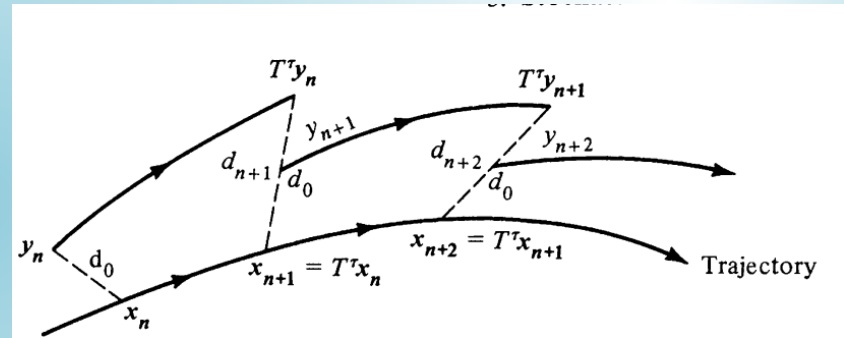
$$d \approx \exp(\lambda_{\max} t)$$

Method for calculation of the largest Lyapunov exponent

$$\lambda_{\max, n} \approx \frac{1}{\Delta t} \sum_n \ln \frac{d_n}{d_0}, \quad d_n = |\vec{y} - \vec{x}|_n,$$

$$\lambda_{\max} = \lim_{n \rightarrow \infty} \lambda_{\max, n}$$

here d_n - distance at time $t = t_n$



renormalization

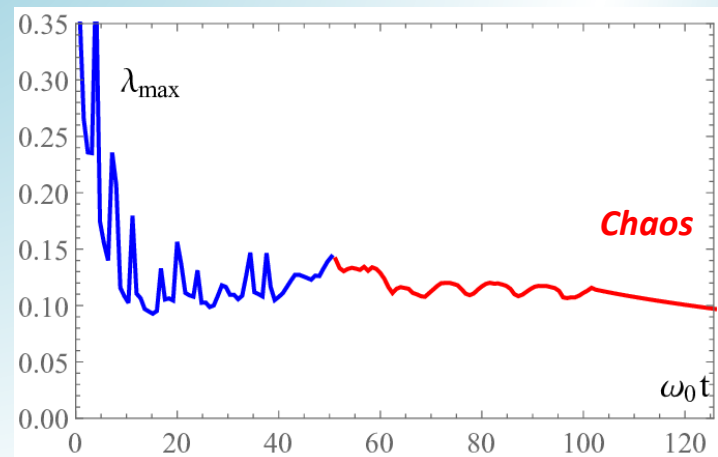
$$\vec{r}_i \leftarrow \vec{R}_i + \frac{\vec{\rho}_i}{a_i}, \quad a_i \equiv \frac{d(t_1)}{d(t_0)}$$

$$d(t) \geq D$$

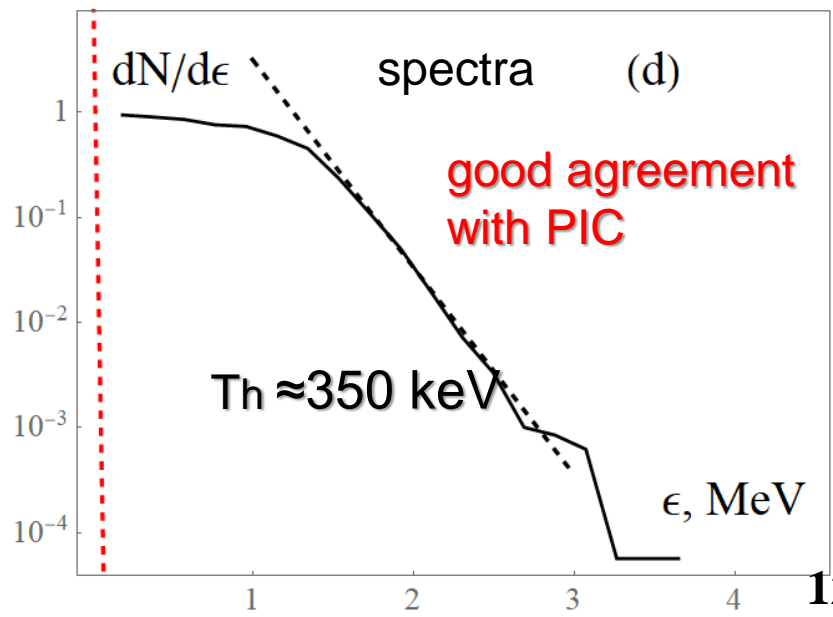
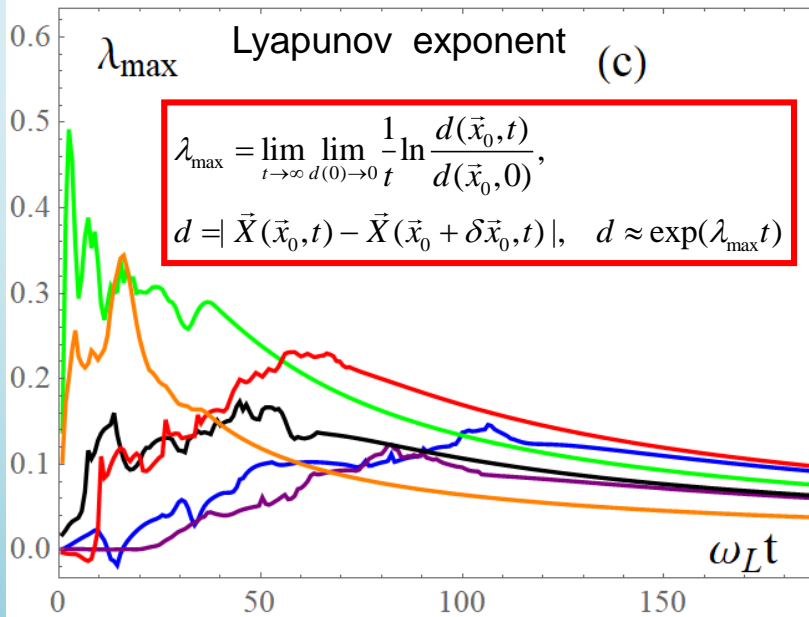
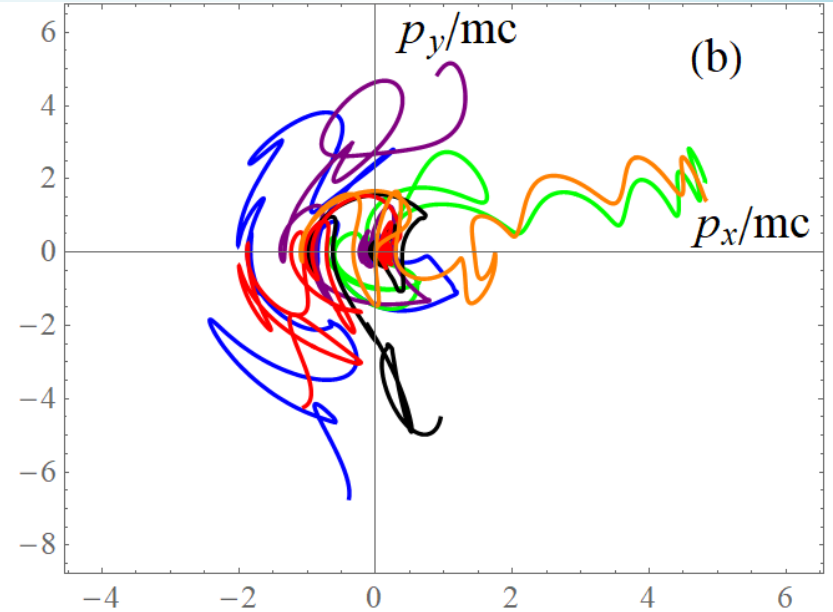
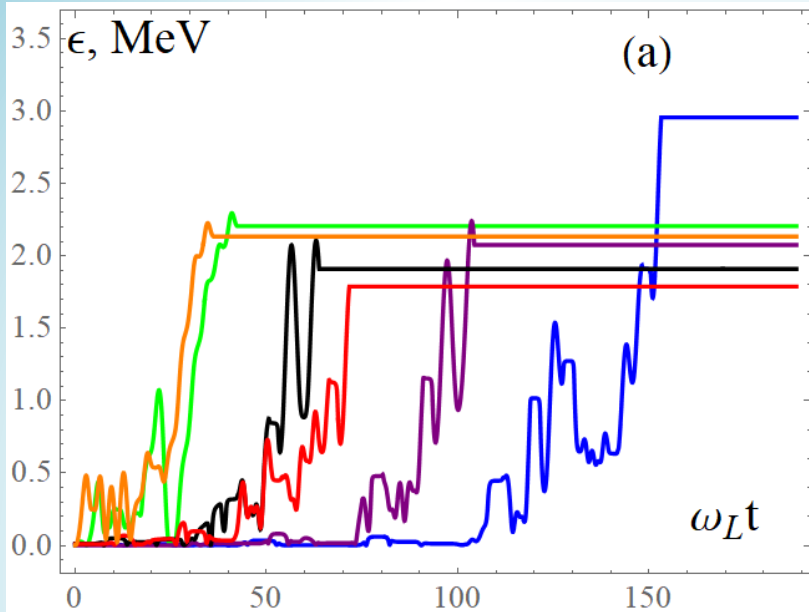
$$\vec{\rho} \equiv \vec{r} - \vec{R}.$$

Criteria of stochastic motion:

$$\lambda_{\max} > 0$$

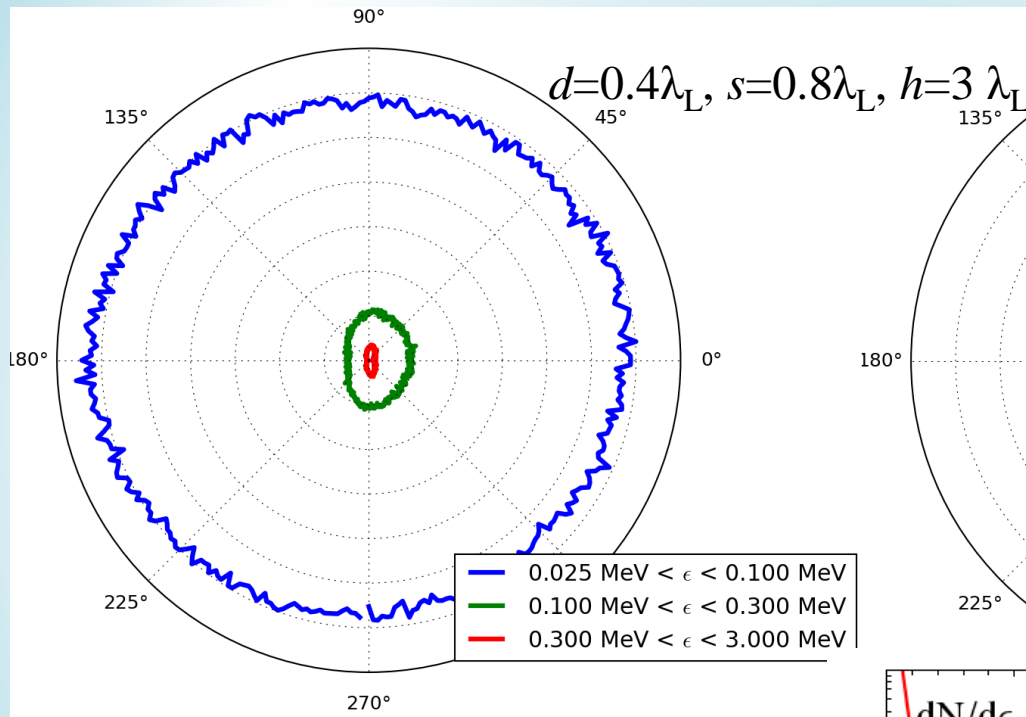


Анализ стохастического нагрева

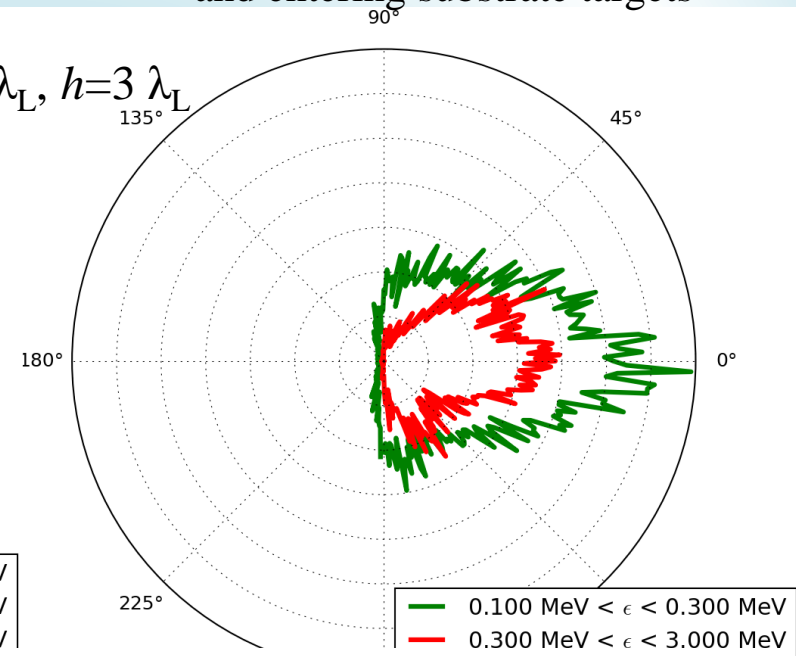


Угловое распределение ускоренных электронов

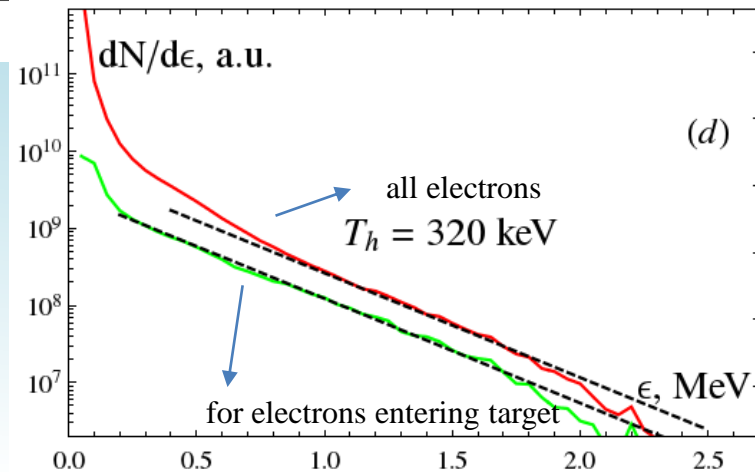
Angular distribution
inside heated domain



Angular distribution
of electrons leaving microstructures
and entering substrate targets



Conversion (energy > 100 keV) reaches
~ 10%.
MA beam current of hot electrons is
formed,
return current heats target to the
temperature of
~ 5 eV in the volume of $30 \times 30 \times 10 \mu\text{m}^3$

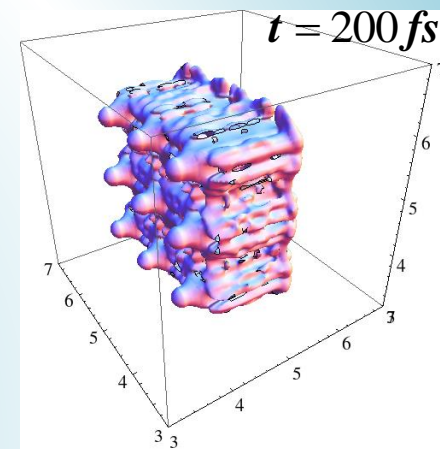
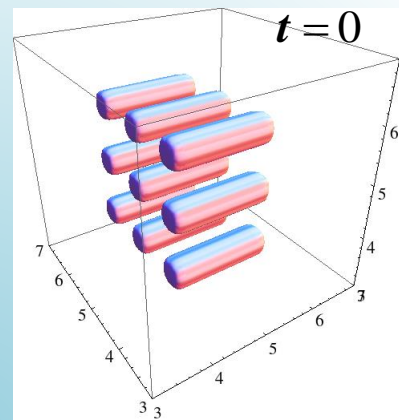
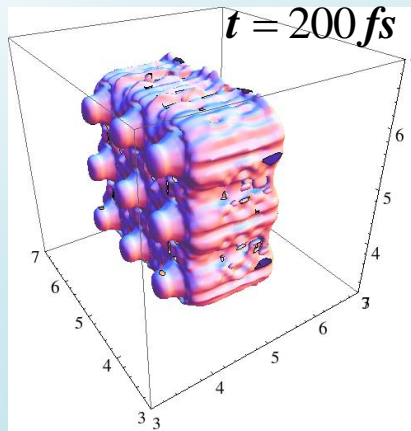
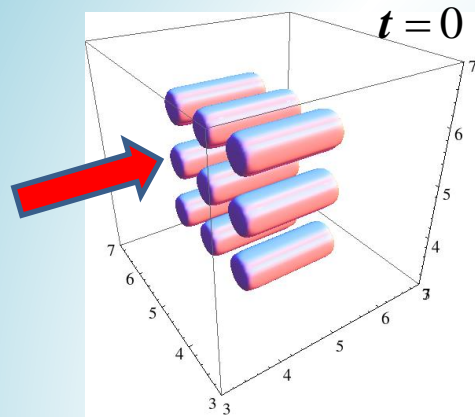


3D моделирование : разлет плазмы

deuterated titanium wires 40% of deuterium 20% D and 20% T.

$$d = 0.4\lambda_L, \quad h = 1.5\lambda_L$$

$$d = 0.3\lambda_L, \quad h = 1.5\lambda_L$$



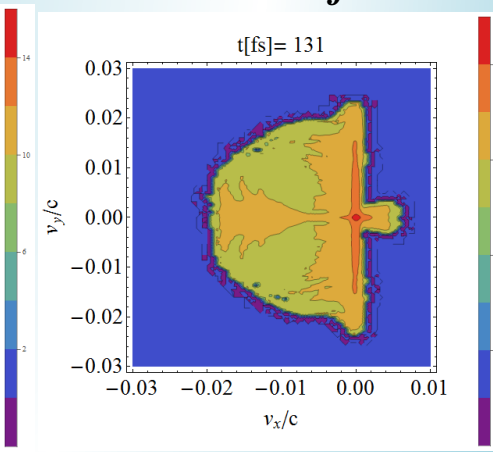
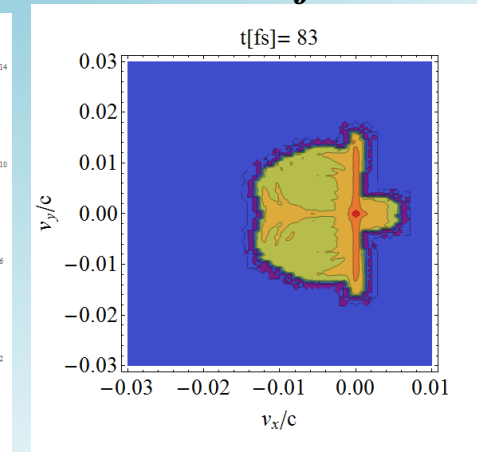
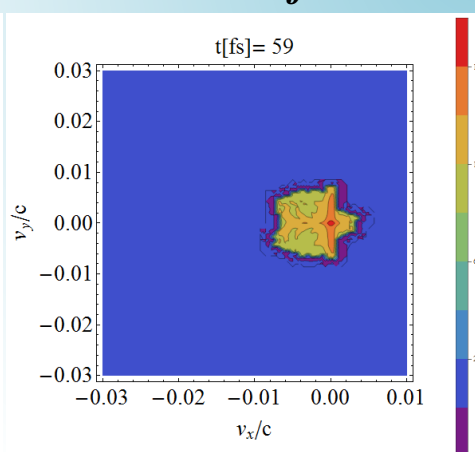
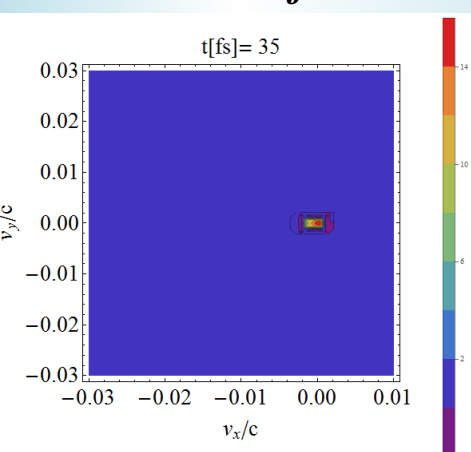
Ion distribution $d^2N/dv_x dv_y$

$t = 35 fs$

$t = 59 fs$

$t = 83 fs$

$t = 131 fs$

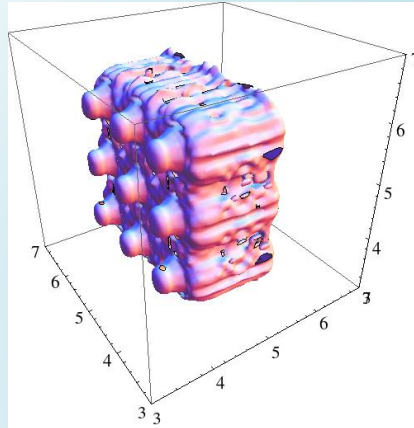
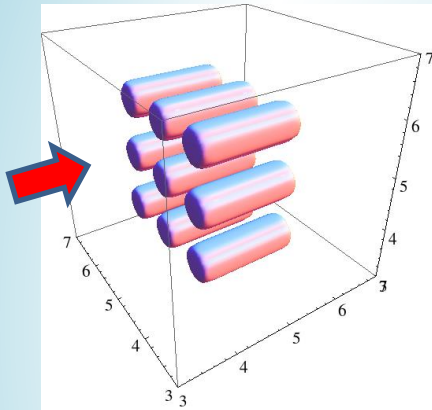


Plasma expands with velocity $\approx 2\mu\text{m/ps}$, The cross section of **DT reaction** is large for deuterium energy of order of 100-500 keV. Deuterons obtain such energy during laser heated cylinder expansion on characteristic scale equal to inter-wire spacing.

Спектры ускоренных дейтронов

We consider acceleration of deuterium and tritium ions implanted into pure metal sub-micro-sized surface structures

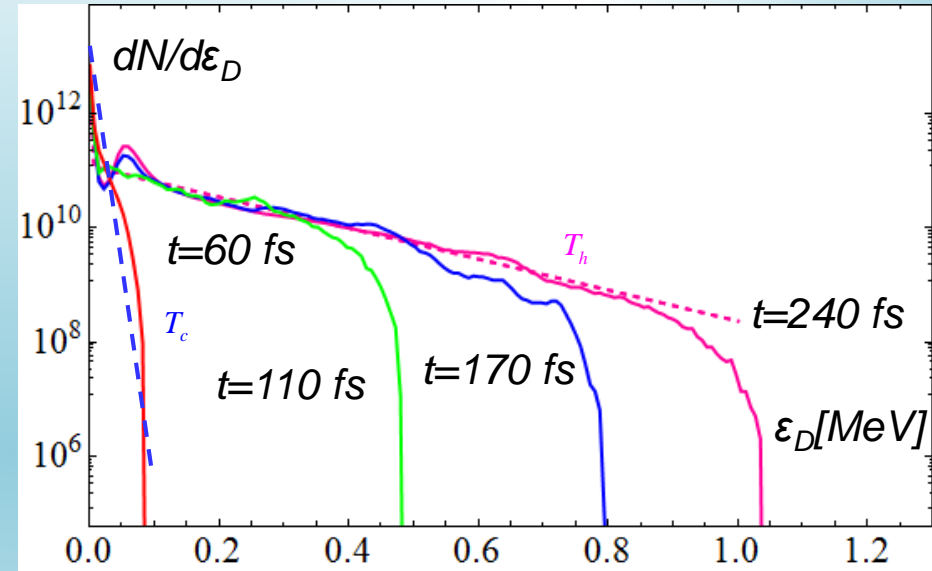
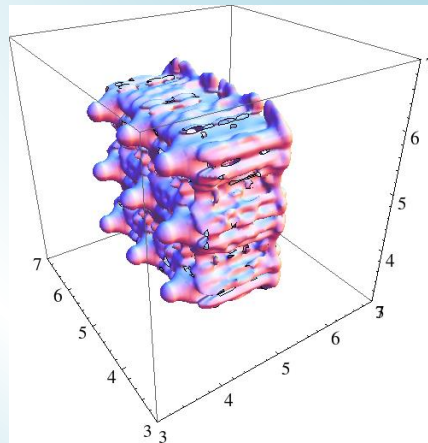
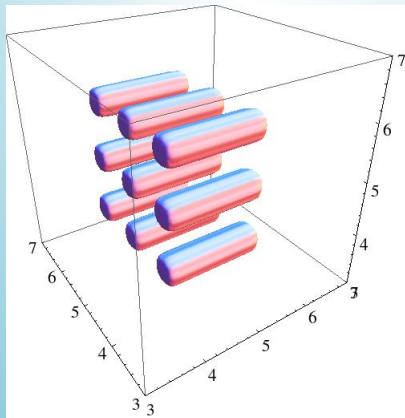
$t=0$ $d=0.4 \lambda_L, h=2 \lambda_L$ $t=200$ fs



$t=0$

$d=0.3 \lambda_L, h=2 \lambda_L$

$t=200$ fs Conversion of energy into ions is about 6 ($d=0.4 \lambda_L$) to 10 % ($d=0.3 \lambda_L$)



Approximation for spectrum

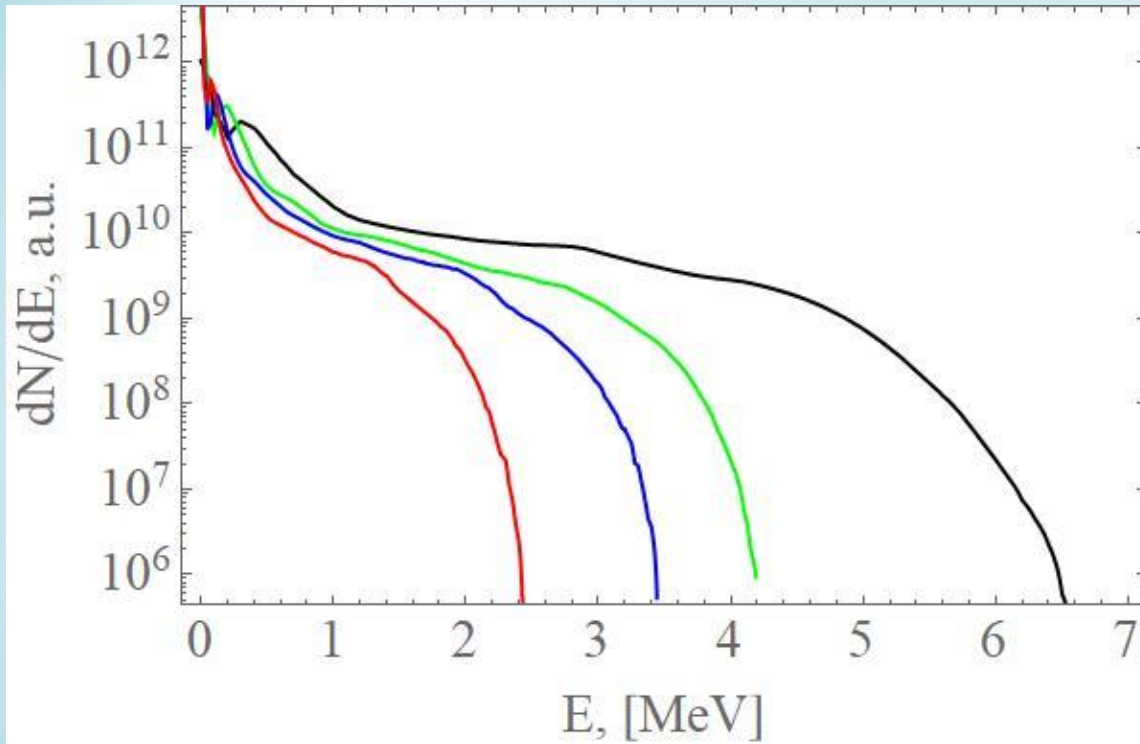
$$\frac{dN}{d\varepsilon_2} = \theta(\varepsilon_{ch} - \varepsilon_2) C n_{c0} \exp\left(\frac{-\varepsilon_2}{Z_2 T_c}\right) + \theta(\varepsilon_2 - \varepsilon_{ch}) C n_{h0} \exp\left(\frac{-\varepsilon_2}{Z_2 T_h}\right),$$

$$\varepsilon_{ch} = Z_2 T_c \ln(n_{c0}/n_{h0}),$$

V.F.Kovalev, S.G.Bochkarev and V.Yu.Bychenkov,
Quantum Electron., **47**, 1023 (2017).

Спектры ускоренных дейтронов от E_L

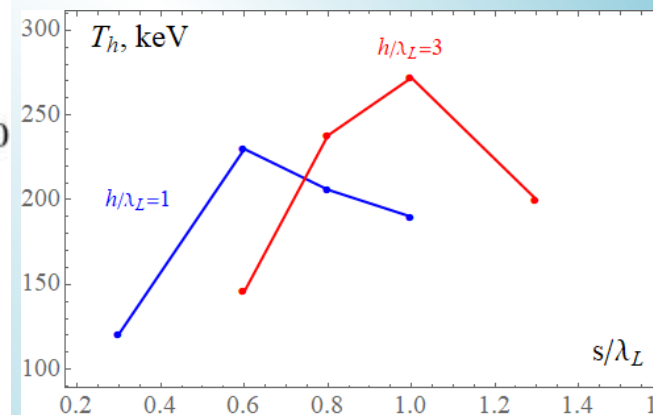
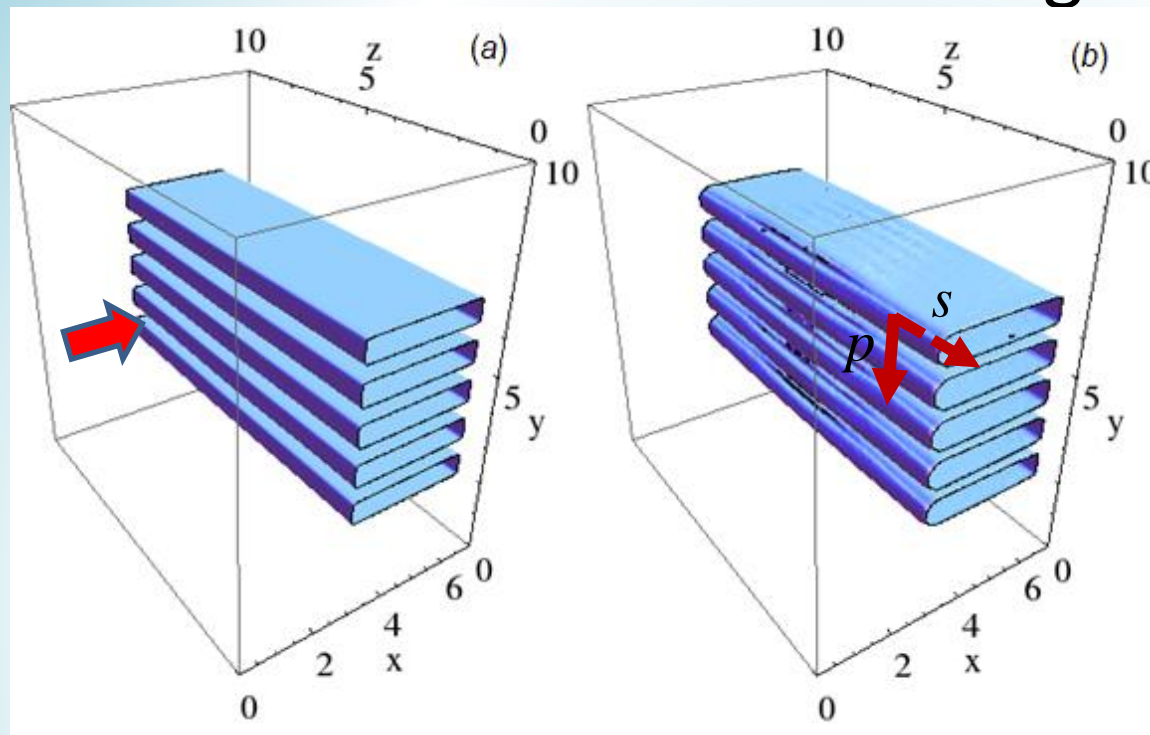
$D_L = 4 \lambda_L$ (FMHW) duration – 30 fs



$E_L = 27$ mJ - red, 54 mJ - blue, 108 mJ –green line и 270 mJ – black line

$$\epsilon_{max} = 2T_h (\ln(\sqrt{2}t_{acc} \omega_{Dh}/\sqrt{e}))^2$$

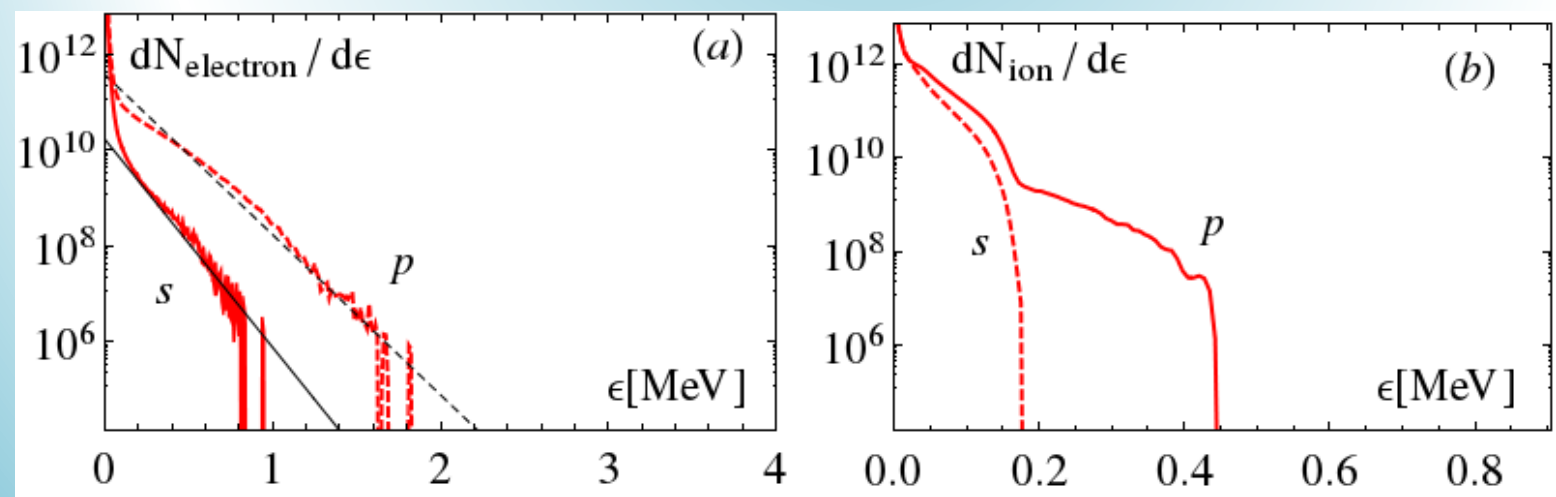
Multi sheet target



$T_h \approx 270$ keV for $h = 3\lambda_L$, $s = 1\lambda_L$,
 $d = 0.4\lambda_L$ that is 20% less than for microwire target

$$T_h^{sheet} / T_h^{wire} \approx \pi / (1 + s/d)$$

Difference between p and s polarization of laser pulse



Расчет выхода DD и DT реакции

$$Y \equiv \frac{N}{N_{i0}} = \frac{1}{N_{i0}} \int_0^\infty d\epsilon \frac{dN_i}{d\epsilon} n_a \int_0^\epsilon d\epsilon' \sigma(\epsilon') \left| \frac{d\epsilon'}{dr} \right|^{-1}$$

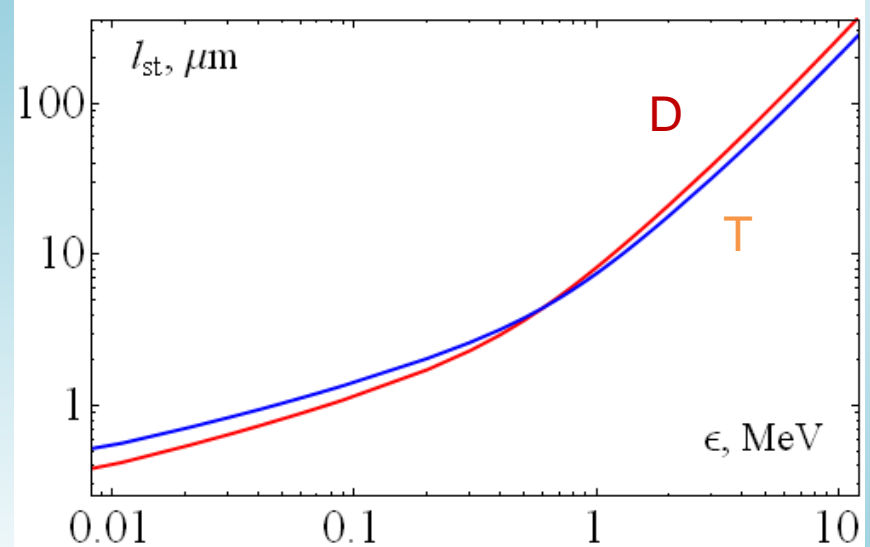
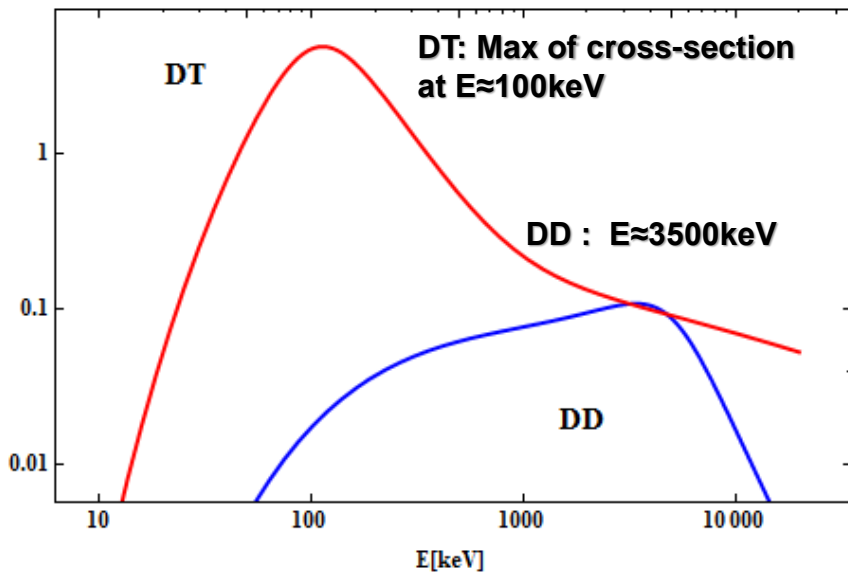
The target consist from titanium and 40% of deuterium or 20% D and 20% T.

$D+D \rightarrow {}^3\text{He} + n + 3.27 \text{ MeV}$, $E_n = 2.45 \text{ MeV}$,

$D+T \rightarrow {}^4\text{He} + n + 17.6 \text{ MeV}$, $E_n = 14.1 \text{ MeV}$,

Cross-sections $D(d,n){}^3\text{He}$, $T(d,n){}^4\text{He}$
from NRS book

Stopping length of Deutrons in Titanium
(experimental data)



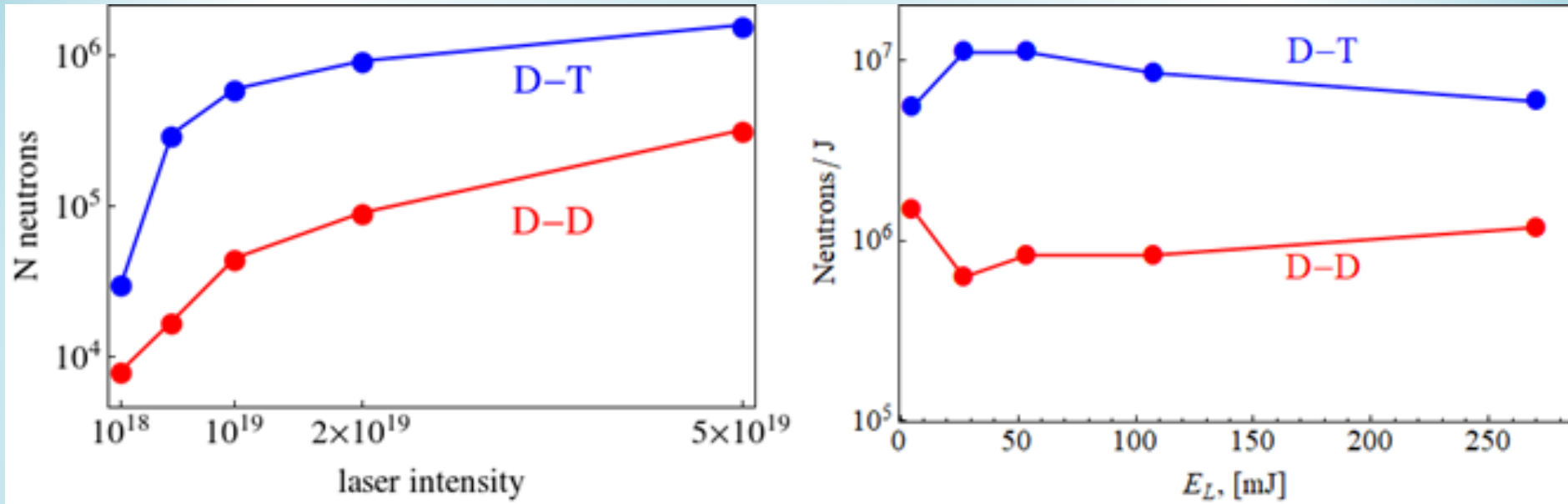
Результаты оптимизации для $E_L = 5$ мДж

№	тип мишень/лазер	средняя плотность, n_{av}/n_0	высота, h/λ_L	диаметр, d/λ_L	абсолютный выход DD	выход DD на 1 Дж
1	проволоки/I	0,07	1,5	0,3	5×10^3	10^6
2	проволоки/I	0,13	1,5	0,4	5×10^3	10^6
3	проволоки/II	0,28	3	0,6	10^4	2×10^6
4	проволоки/II	0,04	7,5	0,4	5×10^3	10^6
5	слои/I,p	0,2	3	0,2	4×10^3	8×10^5
6	слои/I,p	0,4	3	0,4	2×10^3	4×10^5
7	слои/I,s	0,4	3	0,4	5×10^2	10^5

$$N_D \sim 3 \cdot 10^{10}$$

Выход нейтронов (микро-цилиндры)

$$N = V \sigma_0 v_D t_r n_a n_D, \quad t_r \approx l_{st}^D / v_D$$



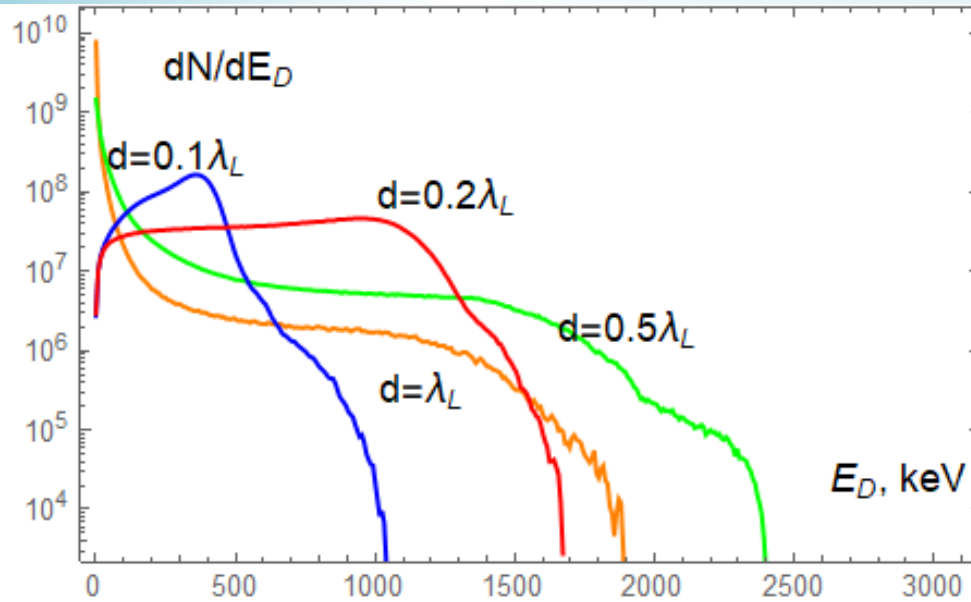
$$D_L = 4 \lambda_L \text{ (FMHW)}, \quad \tau = 30 \text{ fs}$$

$$N_D \sim 3 \cdot 10^{10} \text{ (} E_d > 50 \text{ keV, } I_L \approx 10^{18} \text{ Wcm}^{-2} \text{), } dN_D/N_{D0} \approx 30\text{-}60 \%$$

Neutron yield (25 mJ, 0.1 kHz)

$5 \cdot 10^7$ neutrons/s (DD) and 10^9 neutrons/s (DT)

Генерация нейтронов из микро-кластеров

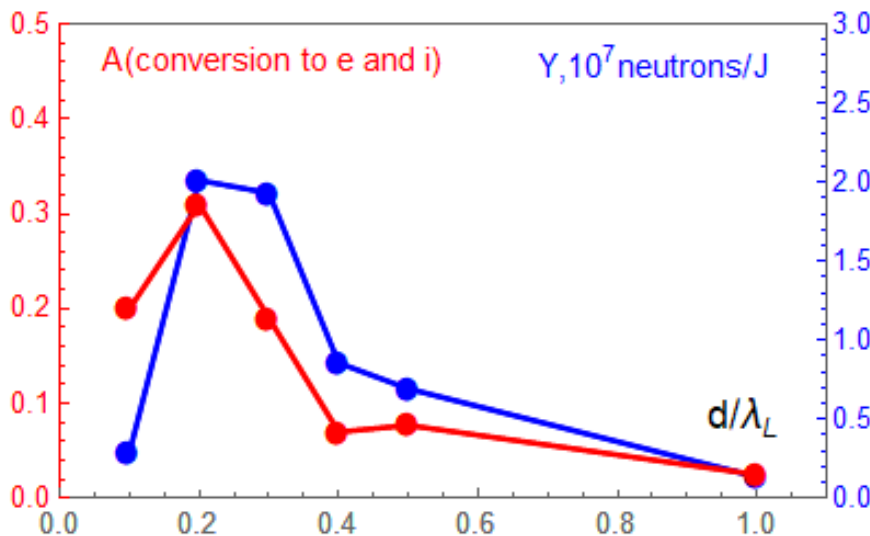


3D3V PIC particles per cell,
 deuterium clusters,
 Box size: $12 \lambda_L \times 6 \lambda_L \times 6 \lambda_L$,
 Resolution $0.01 \lambda_L \times 0.01 \lambda_L \times 0.01 \lambda_L$,
 Linearly polarized laser pulse,
 $I = 2 \cdot 10^{18} \text{ W/cm}^2$, $\tau = 30 \text{ fs}$, **wide laser pulse**

$$n_{av} / n_{cr} \approx \pi d^3 / 6s^3$$

$$n_{av} = 0.12 n_{cr}$$

Maximum conversion coefficient
 corresponds to the maximum
 neutron yield



Выводы

- Объемный стохастический нагрев микро-структурированной мишени, генерация супер-пондеромотоновых электронов
- Эффективное ускорение дейтронов, повышение эффективности термоядерных реакций
- Выход нейтронов для лазера 25мДж, 1кГц $5 \cdot 10^7$ (DD) и $\cdot 10^9$ (DT) нейтронов/сек
- Применение микро-слоев более перспективно, тк технологических слои легче произвести

Thank you very much for your attention!

**This work was supported by the Russian Science
Foundation, Grant # 17-12-01283**

D.A. Gozhev, S.G. Bochkarev, N.I. Busleev., A.V. Brantov, S.I. Kudryashov,
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S.G. Bochkarev, A.V. Brantov, D. A. Gozhev

Journal of Russian Laser Research **42**, (2021), in press.

