

Кинетические эффекты и неустойчивости при взаимодействии мощных потоков излучения с плазмой

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"Исследования в области физики высоких плотностей энергии лазерными и электрофизическими методами"



Физика высоких плотностей энергий в ФИАН и ВНИИА

ICF related

Kinetic effects of laser-plasma interaction in:

mode coupling

parametric instabilities

self-focusing

ion-acoustic instability, anomalous absorption

Kinetic transport phenomena:

Nonlocal heat wave propagation

Hot spot or temperature profile relaxation

Waves in heat carrying plasma

Ion separation in shock wave

Radiative heat transport instability

Extreme light related

Laser-target design for maximization of:

electron energy

electron number

ion energy

ion number

gamma quanta energy

gamma quanta number

yield of nuclear reactions

collision of relativistic plasmas

X-ray pulse interaction with matter

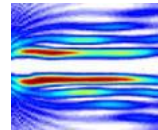
Relativistic self-focusing

Magnetic field generation

Relativistic plasma resonance and harmonics

Parametric instabilities in a corona

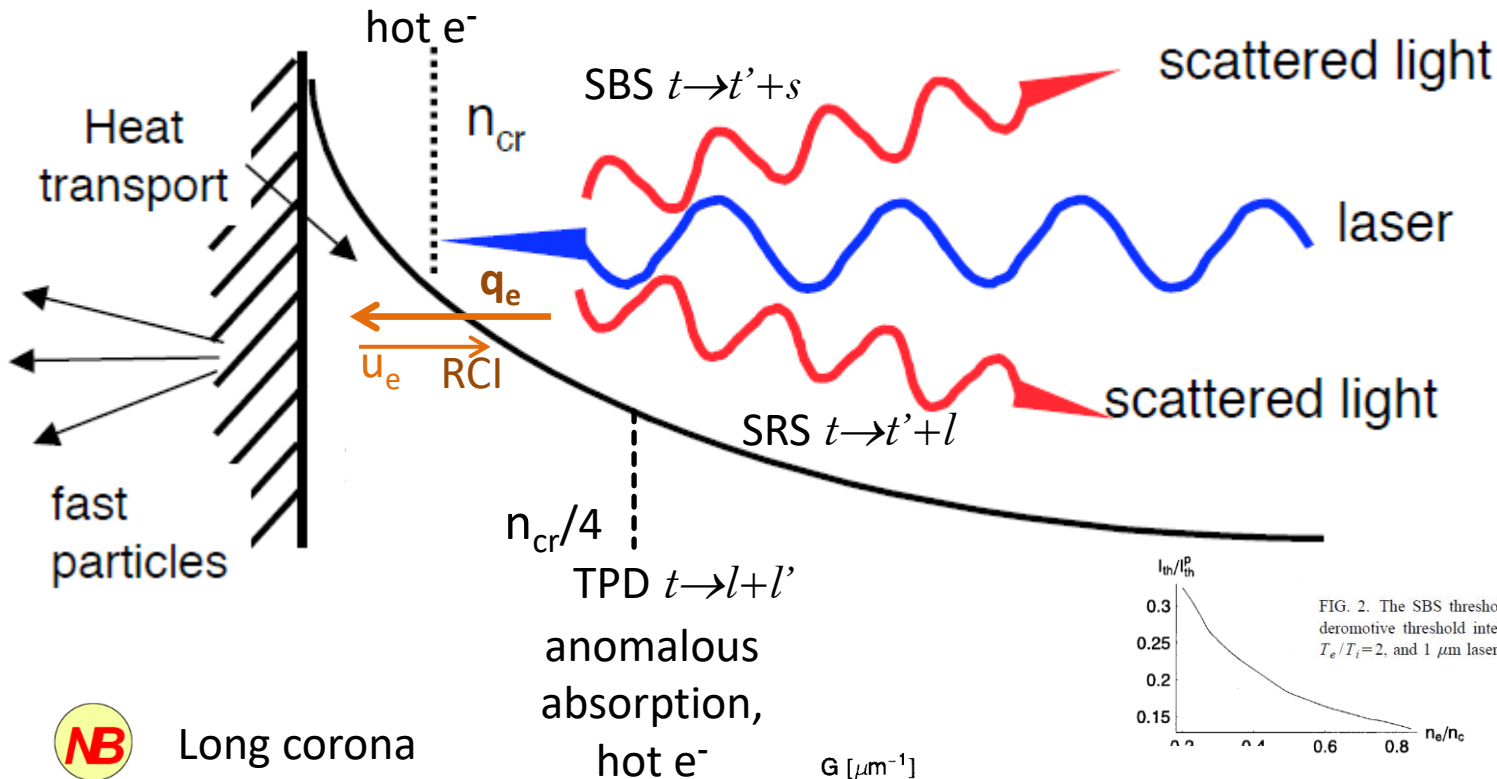
Parametric $t \rightarrow l + s$
 decay $t \rightarrow l + a$
 anomalous
 absorption,



filamentation instability

$$A_k \approx \frac{1}{2} + Z \left(\frac{0.074}{x^2} + \frac{0.88}{x^{4/7}} + \frac{2.54}{1 + 5.5x^2} \right)$$

$$x = \sqrt{Z} k \lambda_{ei}$$



Long corona

PRL 120, 055001 (2018)

Origins and Scaling of Hot-Electron Preheat
 in Ignition-Scale Direct-Drive ICF Experiments,
 M. J. Rosenberg et al.

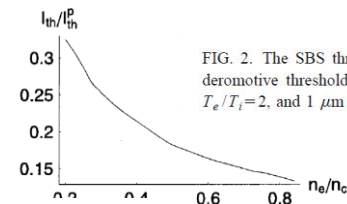


FIG. 2. The SBS threshold intensity normalized to the collisionless ponderomotive threshold intensity I_{th}^p for $A=197$ (gold), $Z=64$, $T_e=2$ keV, $T_e/T_i=2$, and $1 \mu\text{m}$ laser wavelength.

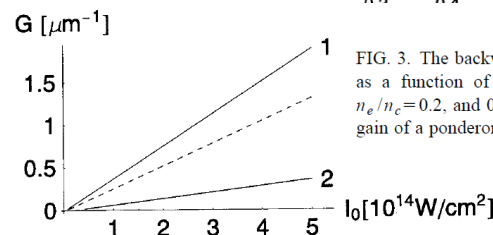
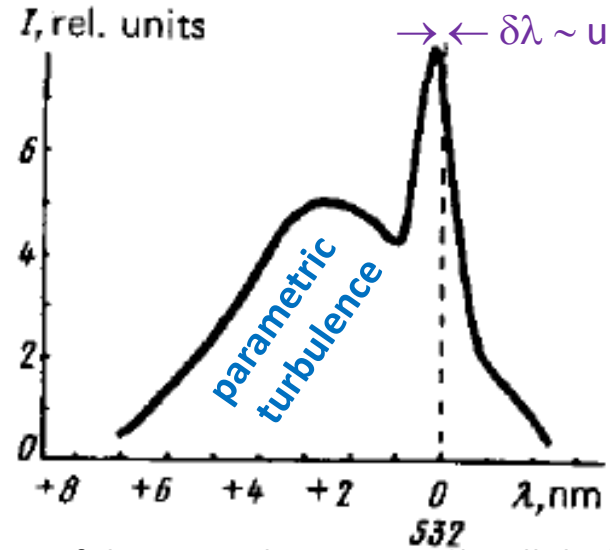
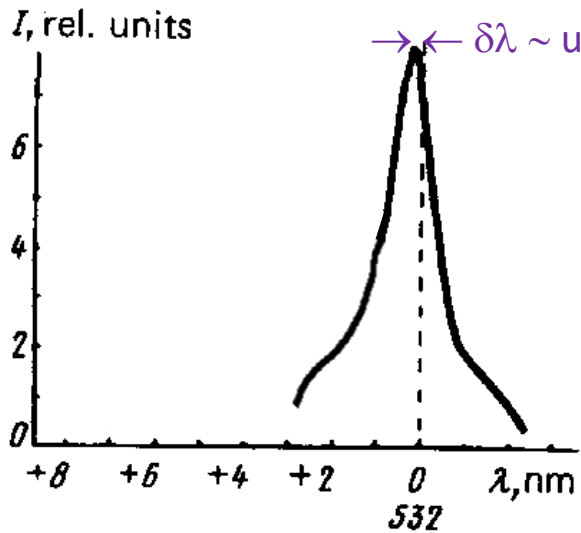
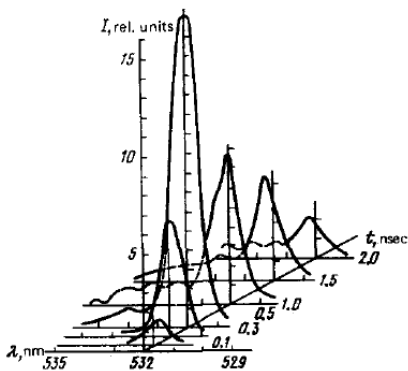


FIG. 3. The backward SBS gain per unit length in a plasma with cold ions as a function of laser intensity for $A=197$ (gold), $Z=64$, $T_e=2$ keV, $n_e/n_c=0.2$, and $0.35 \mu\text{m}$ laser wavelength (line 1) in comparison with the gain of a ponderomotive SBS (line 2) and the result of Ref. 9 (dashed line).

2 ω from laser-produced plasma 1976 – 1977, Lebedev Institute



Spectrogram of the second harmonic line for a glass shell target of the 94 μ m diameter and wall thickness 0.7 μ m



$\delta\lambda < 0, u > 0$
 $\delta\lambda > 0, u < 0$

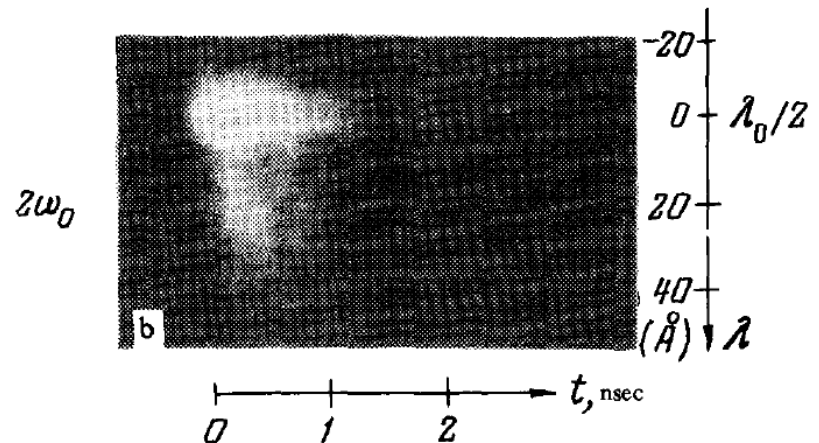
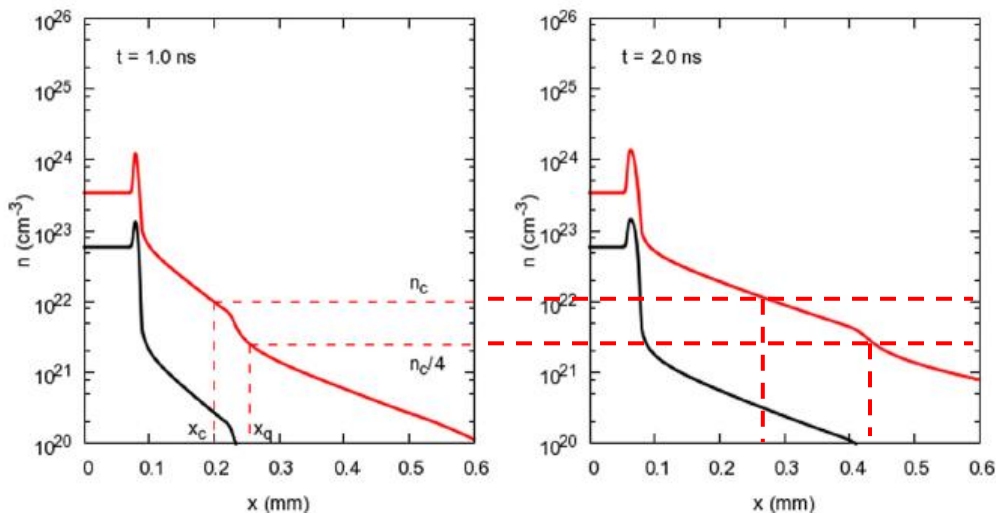


FIG. 10. Spectral distributions of the harmonic radiation

Near critical density. Renaissance in parametric decay ?

Anomalous absorption? Hot electrons?

Gold hohlraum wall simulation for incident laser with $I=10^{15} \text{W/cm}^2$ and $\lambda=(1/3) \mu\text{m}$



C. Thoma, D. R. Welch, R. E. Clark, D. V. Rose, I. E. Golovkin, PoP 24, 062707 (2017)

$l \sim 0.1 \text{mm}$

Janus laser, PRL (1978)

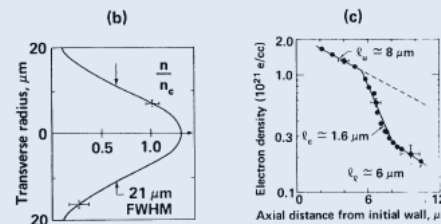
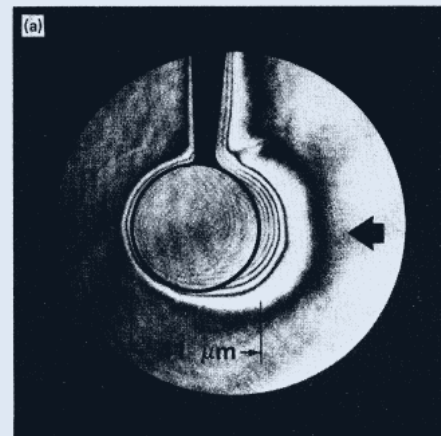


FIG. 1. (a) Interferogram at peak irradiation of a 41- μm -diam ball. $I \approx 3 \times 10^{14} \text{W/cm}^2$. (b) Transverse electron density profile at an axial position 4 μm from the initial target wall. (c) Density profile on axis, demonstrating steepening due to radiation pressure. Solid lines are best fit; e -folding scale lengths l_u , l_c , and l_l are indicated for the upper, critical, and lower density regions. Typical error bars are shown in (b) and (c); $n_c = 10^{21} \text{e/cm}^3$.

0.26 μm probe pulse,

$l = 1.6 \mu\text{m}$ profile steepening

Всплеск интереса к поглощению на ионно-звуковой турбулентности

Re-examining our inhibitions: A speculative re-analysis of data from Au spheres illuminated by the URLLE Ω laser Presented to: APS/DPP Savannah, GA, Paper # UO7.00003 M. D. (“Mordy”) Rosen, J. S. Ross, C. A. Thomas LLNL, 11/20/15

“... ion acoustic turbulence ... also increase absorption. This increase in absorption, applied (speculatively) close by the critical surface, can begin to match the Au sphere x-ray emission, as well as a preponderance of the ZTe data.”

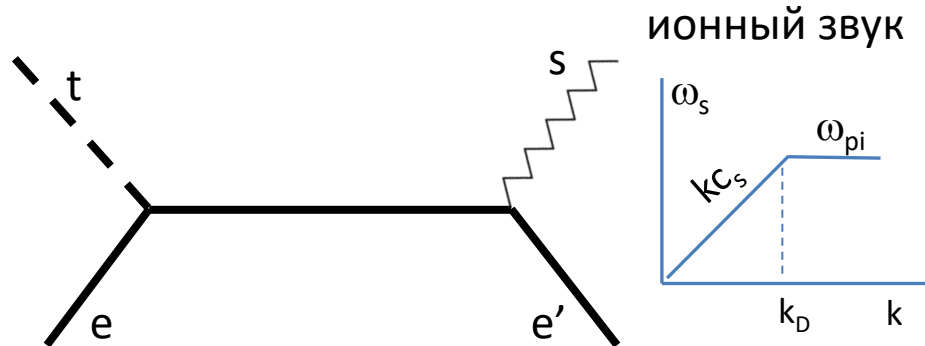
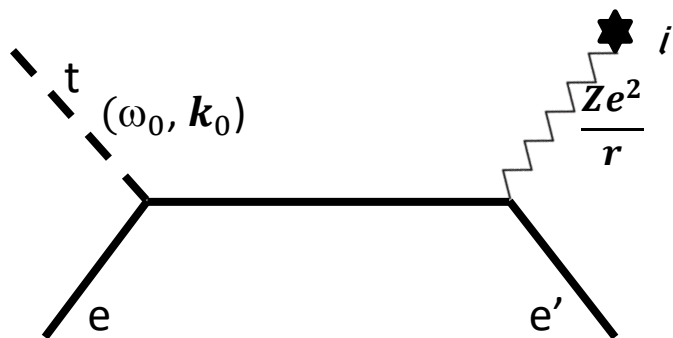
46th Annual Anomalous Absorption Conference, Old Saybrook, CT, USA, May 1-6, 2016, Thomson scattering characterization of a 1D Hohlraum wall surrogate (a Au sphere) for improved understanding of hohlraum physics, J. S. Ross, G. Swadling, M. D. Rosen, K. Widmann, B. Heeter, J. Moody

“An experimental campaign was completed at the Omega laser facility ad-hoc anomalous absorption (presumably due to the same ion acoustic turbulence that leads to the flux limitation) near the critical surface, is considered.”

Some speculations relating to experiments aimed at IAT and its effects
R. Paul Drake, University of Michigan, March 18, 2016

“An ideal experiment would observe consequences of turning IAT on and off.”

Обратное тормозное поглощение. Поглощение на усиленных флуктуациях



$$\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \frac{\partial f_e}{\partial \mathbf{r}} - \frac{e}{m_e} \tilde{\mathbf{E}} \cdot \frac{\partial f_e}{\partial \mathbf{v}} = C_{ei}[f_e]$$

$$\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \frac{\partial f_e}{\partial \mathbf{r}} - \frac{e}{m_e} \tilde{\mathbf{E}} \cdot \frac{\partial f_e}{\partial \mathbf{v}} = \frac{\partial}{\partial v_i} D_{ij}^{(e)} \frac{\partial f_e}{\partial v_j}$$

$$C_{ei}[f] = \frac{\partial}{\partial v_i} D_{ij}^{(e)} \frac{\partial f_e}{\partial v_j} = \frac{m_e}{m_i} \lll 1$$

$$D_{ij}^{(e)} = \frac{e^2}{2\pi m_e^2} \int d\mathbf{k} \frac{k_i k_j}{k^2} \frac{\omega_s^3}{\omega_{Li}^2} N(k) \delta(\omega_s - k v)$$

$$= v_{st} \frac{v_{Te}^3}{v^3} \frac{\partial}{\partial \cos \theta} \sin^2 \theta \frac{\partial f_e}{\partial \cos \theta}, \quad v_{st} = \frac{2\pi z e^4 n_e \Lambda}{m_e^2 v_{Te}^3}$$

$$\frac{\partial}{\partial v_i} D_{ij} \frac{\partial}{\partial v_j} = \frac{1}{v \sin \theta} \frac{\partial}{\partial \theta} \left[\sin \theta \left(\frac{1}{v} D_{\theta\theta} \frac{\partial}{\partial \theta} \right) \right]$$

$$v_{ei} \longleftrightarrow \omega_{pe} \frac{E^2}{4\pi n_e \kappa T_e} \longleftarrow \frac{E^2}{4\pi} = \int \frac{d\mathbf{k}}{(2\pi)^3} \underbrace{\omega_s(k) N(k)}_{W(k)}$$

Поглощение на нетепловых флуктуациях

$$\sigma = \frac{e^2 n_e}{m \omega_0} \left[i + \frac{\nu_{ei}}{\omega_0} \frac{1}{\Lambda_c n_i} \int_0^\infty d\omega' \int_0^{k_{max}} \frac{dk'}{k'} \frac{\int d^3 p \delta(\omega' - \mathbf{k}' \mathbf{v}) f_i}{|\epsilon(\omega', k')|^2} \right] \quad T_i \rightarrow 0 \quad \sigma = \frac{e^2 n_e}{m \omega_0} \left[i + \frac{\nu_{ei}}{\omega_0} \right]$$

$$\frac{\int d^3 p \delta(\omega' - \mathbf{k}' \mathbf{v}) f_i}{|\epsilon(\omega', k')|^2} \propto (\delta n_i^2)_{\omega', k'}$$

$$\nu_{ei} \rightarrow \nu_{eff} \propto \int d\mathbf{k} (\delta n_i^2)_{\mathbf{k}'} \propto \int d\mathbf{k} W(\mathbf{k}') \propto \frac{E^2}{4\pi}$$

THE PHYSICS OF FLUIDS

VOLUME 6, NUMBER 3

MARCH 1963

Effect of Ion Correlations on High-Frequency Plasma Conductivity

JOHN DAWSON AND CARL OBERMAN

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey

(Received 13 August 1962)

In an earlier work the ac conductivity of a plasma was investigated by means of an elementary model. The validity of this model has been borne out by a rigorous treatment of plasma at thermal equilibrium. The elementary model is now extended to include the effects of ion correlations for arbitrary fixed ion distributions. For thermal equilibrium correlations it is found that the ion shielding reduces the maximum effective impact parameter by the factor $(1 + Z)^{\frac{1}{2}}$ (i.e., both ions and electrons contribute to the shielding) for frequencies low compared to the plasma frequency ω_p . For frequencies high compared to ω_p , the previous results obtain. The resistance due to the excitation of longitudinal waves at frequencies just in excess of ω_p is reduced by the factor $(1 + Z)^{-1}$. However, if large-amplitude (nonthermal) ion fluctuations are present, the longitudinal wave contribution to the resistance may be greatly enhanced.

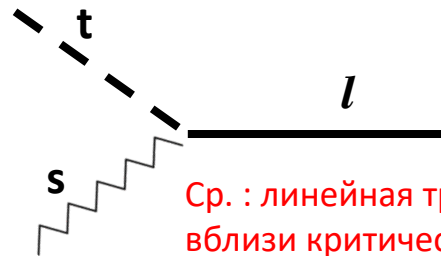
Статические
флуктуации,
 $\omega'=0$

Эффективная частота столкновений

$$\frac{\partial I}{\partial t} + \mathbf{v}_0 \frac{\partial I}{\partial \mathbf{r}} = -\frac{\omega_{pe}^2}{\omega_0^2} (\nu_{ei} + \nu_{eff} + \nu_{eff}^R) I$$

$$\nu_{eff} = \sqrt{\frac{\pi}{2}} \frac{\omega_{pe}^2}{\omega_{pi}^2} \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{(\mathbf{e}_0 \cdot \mathbf{k})^2 \omega_s^3 N(\mathbf{k})}{k^3 v_{Te} n_e T_e}$$

ν_{eff}^R ?



$$\begin{aligned} \omega_l &= \omega_0 \pm \omega_s \\ \mathbf{k}_l &= \mathbf{k}_0 \pm \mathbf{k}_s \\ n_e &\approx n_c \end{aligned}$$

Ср. : линейная трансформация
вблизи критической плотности

THE PHYSICS OF FLUIDS

VOLUME 6, NUMBER 3

MARCH 1963

In addition to increasing the wave resistance, the coefficient of absorption from transverse to longitudinal wave and the conversion of longitudinal waves to transverse waves is increased by the factor β

$$\beta \approx \delta^2 \bar{n}_i / 4\pi \bar{k}^3$$

Резонансное турбулентное поглощение

Anomalous heating of plasma by laser irradiation

P Kaw, J Dawson, W Kruer, C Oberman and E Valeo Sov. J. Quantum Electron. 1, 205 (1971)

When an intense electric field oscillating near the electron plasma frequency is applied to a plasma, it excites parametric instabilities which drive up the ion density fluctuations. The presence of moderate ion density fluctuations leads to a strong enhancement of the high-frequency resistivity around the plasma frequency and hence to anomalous plasma heating. The enhancement of the resistivity, which can be physically attributed to a collective process involving the conversion of the electromagnetic wave energy into longitudinal plasma waves by a resonant mode coupling process involving the ion waves, can typically be many orders of magnitude. An account is given of evidence based on computer simulations, laboratory experiments with microwaves done elsewhere and in Princeton, and on experiments involving the radio wave propagation in ionosphere, which establishes the existence of such an effect beyond doubt. A semiquantitative theory to explain the laboratory and computer experiments is also presented.

Laser light absorption by short wavelength ion turbulence

R. J. Faehl* and W. L. Kruer

Lawrence Livermore Laboratory, University of California, Livermore, California 94550
(Received 3 November 1975; final manuscript received 13 September 1976)

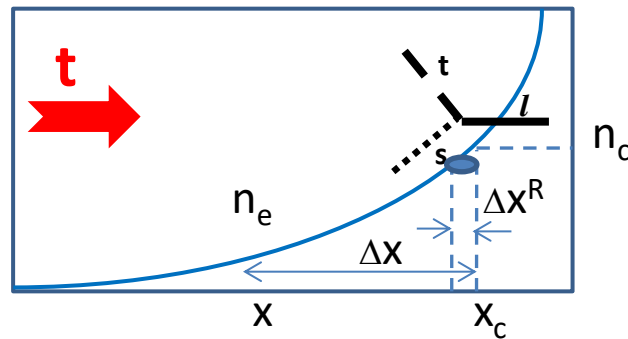
The absorption of laser light due to short wavelength ion fluctuations ($\lambda \sim 10$ electron Debye lengths) is considered. The effective collision frequencies and heated electron distributions are computed as a function of plasma density and compared with theory. A simple upper bound to the level of ion turbulence is given, and several sources for the turbulence are discussed briefly. Finally, the absorption due to this mechanism in an inhomogeneous, expanding plasma is calculated by putting the estimate into a fluid code including wave propagation and density profile steepening by laser light pressure. The results are related to some recent experiments with short-pulse-length Nd laser light.

Phys. Fluids 20, 55 (1977)

Эффективная частота столкновений для резонансного турбулентного поглощения

$$\nu_{eff}^R = -\frac{\omega_{pe}^2}{2} \int \frac{d\mathbf{k}_s}{(2\pi)^3} \frac{(\mathbf{e}_0 \cdot \mathbf{k}_s)^2 \omega_s N(\mathbf{k}_s)}{\omega_0 n_e T_e} \times$$

$$Im \left[\frac{1}{(\mathbf{k}_0 - \mathbf{k}_s)^2 \epsilon_l(\omega_0 - \omega_s, \mathbf{k}_0 - \mathbf{k}_s)} + \frac{1}{(\mathbf{k}_0 + \mathbf{k}_s)^2 \epsilon_l(\omega_0 + \omega_s, \mathbf{k}_0 + \mathbf{k}_s)} \right]$$



$$\Delta x^R \approx 0.3 L$$

$$L = \frac{d}{dx} \ln n_e |_{x=x_c}$$

Поглощение			
	Классическое	Аномальное	
Δx	Кулоновское рассеяние	Рассеяние на турбулентности	Δx
Δx^R	Линейная трансформация	Трансформация на шумах	Δx^R

ИЗТ обратного тока в экспериментах

Plasma Physics, Vol. 22, pp. 81 to 111
© Institute of Physics and Pergamon Press Ltd., 1980.
Printed in Northern Ireland

0032-1028/80/0201-0081\$02.00

THE MEASUREMENT OF ION ACOUSTIC TURBULENCE AND REDUCED THERMAL CONDUCTIVITY CAUSED BY A LARGE TEMPERATURE GRADIENT IN A LASER HEATED PLASMA

D. R. GRAY and J. D. KILKENNY

Blackett Laboratory, Imperial College, London SW7, U.K.

(Received 28 June 1979)

Abstract—An extensive account is given of experiments in which an homogeneous preformed plasma of density $6 \times 10^{16} \text{ cm}^{-3}$ was heated by $10.6 \mu\text{m}$ radiation focussed to $10^{11} \text{ W cm}^{-2}$. Ruby laser scattering gave space and time resolved measurements of the resultant density and temperature, showing large temperature gradients up to $\lambda_e |\nabla T|/T = 0.5$. Enhanced low frequency turbulence was observed.

- Экспериментальная проверка порога неустойчивости;
- Обнаружение пониженной теплопроводности;
- Регистрация существенно нетеплового уровня флуктуаций

Ion-Acoustic Wave Instability Driven by Laser-Driven Return Currents, BAPS.2010.DPP.JO8.2

D.H. Froula, S.X. Hu and, J.F. Myatt (Rochester), J. S. Ross, L. Divol, S. H. Glenzer (LLNL)

Thomson-scattering measurements of the amplitude and frequency of ion-acoustic waves show an instability when the ion-wave damping is reduced. Experimental results from the OMEGA Laser use simultaneous measurements of the electron-plasma wave and ion-acoustic wave features to characterize the plasma (Te, Ti, Z, Ne) and to directly probe the amplitude of the ion-acoustic waves. The ion Landau damping was varied by changing the target material: CH, V, Ag, Au. The amplitude of the plasma wave increased as the ion Landau damping was reduced and became unstable for $Z\text{Te}/\text{Ti} > 50$. As the waves grow to wave-breaking amplitudes, their frequency shifts, and turbulence is expected. These results confirm the speculation that heat-flux--driven ion-acoustic fluctuations exist in laser-produced plasmas.

VOLUME 88, NUMBER 23

PHYSICAL REVIEW LETTERS

10 JUNE 2002

Anomalous Absorption of High-Energy Green Laser Light in High-Z Plasmas

S. H. Glenzer, W. Rozmus, V. Yu. Bychenkov, J. D. Moody, J. Albritton, R. L. Berger, A. Brantov, M. E. Ford, B. J. MacGowan, R. K. Kirkwood, H. A. Baldis, and E. A. Williams

We observe strong anomalous absorption of green laser light in mm-scale high-temperature gold plasmas. Both the laser light absorption and the resulting increase of the electron temperature, which was measured independently with Thomson scattering, have been successfully modeled by including enhanced collisions due to heat-flux driven ion acoustic fluctuations. Calculations that include only inverse bremsstrahlung significantly underestimate the experimental laser absorption and the electron temperature.

Суммарное поглощение на ИЗТ

$$\nu_{eff}^R = \sqrt{\frac{\pi}{2}} \frac{\omega_{pe}^2}{\omega_{pi}^2} \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{(\mathbf{e}_0 \cdot \mathbf{k})^2 \omega_s^3 N(\mathbf{k})}{k^3 v_{Te} n_e T_e}$$

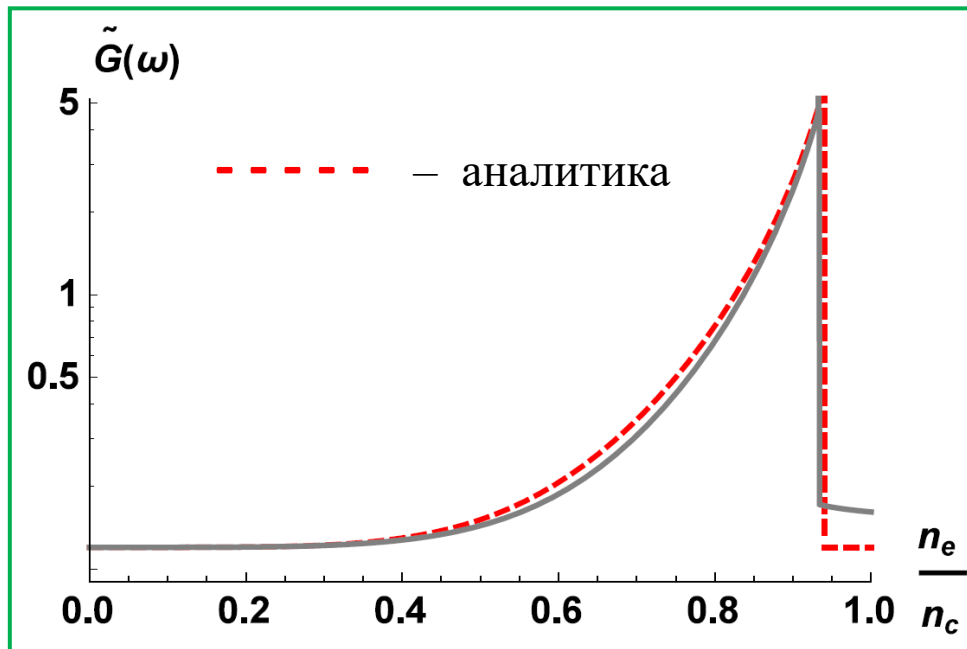
$$\nu_{\parallel, \perp}^R + \nu_{\parallel, \perp} = (\nu^R + \nu) \mu_{\parallel, \perp},$$

$$\nu = \frac{1}{\sqrt{2\pi}} \frac{\omega_{pe}^2}{\omega_{pi}^2} \int_0^\infty k dk \frac{\omega_s^3(k) N(k)}{4\pi n_e T_e} = 0.12 \omega_{pi} \frac{Z T_e}{T_i}$$

$$\nu_{an} \equiv \nu_{eff}^R + \nu_{eff} = \omega_{pi} \frac{Z T_e}{T_i} \tilde{G}(\omega) \left(\mu_{\parallel} (\mathbf{e}_0 \cdot \mathbf{n})^2 + \mu_{\perp} [\mathbf{e}_0 \times \mathbf{n}]^2 \right)$$

$$\tilde{G} = 0.12 + G.$$

$$\nu_{an} \equiv \nu_{eff}^R + \nu_{eff} = \omega_{pi} \frac{Z T_e}{T_i} \tilde{G}(\omega) \left(\mu_{\perp} + \frac{\mu_{\parallel} - \mu_{\perp}}{2k_0^2} [\mathbf{k}_0 \times \mathbf{n}]^2 \right) - \text{усреднение по поляризации}$$



Сравнение полной эффективной частоты столкновений с ее приближенным аналитическим выражением ($k_{\min} \lambda_{De} = 0.15$).

V. Yu. Bychenkov and W. Rozmus
A model of anomalous absorption of laser light on ion acoustic turbulence
 Phys. Plasmas **24**, 012701 (2017)

HOT ELECTRON GENERATION BY RESONANT ANOMALOUS ABSORPTION

$W_l(\mathbf{k}, t)$, generated due to conversion of laser light on ion-acoustic fluctuations in a plasma with near critical electron density ($n_e \simeq n_c$)

$$\frac{\partial W_l(\mathbf{k})}{\partial t} = -2\tilde{\gamma}(\mathbf{k})W_l(\mathbf{k}) + \omega_0 \frac{(\mathbf{k}\mathbf{e}_0)^2}{k^2} \frac{E_0^2}{16n_c T_e} \delta\left(\text{Re}[\epsilon(\omega_0, k)]\right) [W_s(\mathbf{k} - \mathbf{k}_0) + W_s(\mathbf{k} + \mathbf{k}_0)]$$

$$\frac{\partial E_0^2}{\partial t} \frac{1}{8\pi} + \nabla \cdot \mathbf{I} = -\pi\omega_0 \int \frac{d^3k}{(2\pi)^3} \frac{(\mathbf{k}\mathbf{e}_0)^2 \mathbf{W}_s(\mathbf{k})}{2n_c T_e} \left\{ \frac{1}{|\mathbf{k} - \mathbf{k}_0|^2} \delta\left(\text{Re}[\epsilon(\omega_0, |\mathbf{k} - \mathbf{k}_0|)]\right) + \frac{1}{|\mathbf{k} + \mathbf{k}_0|^2} \delta\left(\text{Re}[\epsilon(\omega_0, |\mathbf{k} + \mathbf{k}_0|)]\right) \right\} \frac{E_0^2}{8\pi} \equiv -\nu_{eff}^R \frac{E_0^2}{8\pi}$$

$$\frac{\partial \langle |E_l^2| \rangle}{\partial t} \frac{1}{4\pi} = -2 \int \frac{d^3k}{(2\pi)^3} \tilde{\gamma}(\mathbf{k}) W_l(\mathbf{k}) + \omega_0 \frac{E_0^2}{16n_c T_e} \int \frac{d^3k}{(2\pi)^3} \frac{(\mathbf{k}\mathbf{e}_0)^2}{k^2} \delta\left(\text{Re}[\epsilon(\omega_0, k)]\right) \times [W_s(\mathbf{k} - \mathbf{k}_0) + W_s(\mathbf{k} + \mathbf{k}_0)] \equiv -2 \int \frac{d^3k}{(2\pi)^3} \tilde{\gamma}(\mathbf{k}) W_l(\mathbf{k}) + \nu_{eff}^R \frac{E_0^2}{8\pi}$$

$$\boxed{\frac{\partial}{\partial t} \left(\frac{E_0^2}{8\pi} + \frac{\langle |E_l^2| \rangle}{4\pi} \right) + \nabla \cdot \mathbf{I} = -2 \int \frac{d^3k}{(2\pi)^3} \tilde{\gamma}(\mathbf{k}) W_l(\mathbf{k})}$$

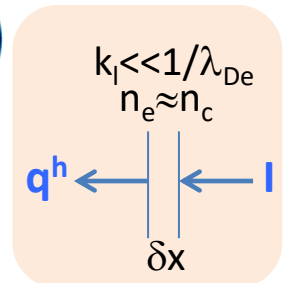
$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \frac{\partial}{\partial \mathbf{r}} \right) f^h = \frac{\partial}{\partial v_i} D_{ij} \frac{\partial f^h}{\partial v_j}, \quad D_{ij} = \frac{e^2}{2\pi m_e^2} \int d^3k \frac{k_i k_j}{k^2} W_l(\mathbf{k}) \delta(\omega_p - \mathbf{k}\mathbf{v})$$

$$\frac{\partial}{\partial t} \frac{3}{2} n^h T^h + \nabla \cdot \mathbf{q}^h = 2 \int \frac{d^3k}{(2\pi)^3} \tilde{\gamma}(\mathbf{k}) W_l(\mathbf{k}), \quad \tilde{\gamma} = \frac{\pi}{n^h} \frac{\omega_p^3}{k^2} \int d^3v \delta(\omega_p - \mathbf{k}\mathbf{v}) \left(\mathbf{k} \cdot \frac{\partial f^h}{\partial \mathbf{v}} \right)$$

$$\boxed{\frac{\partial}{\partial t} \left(\frac{E_0^2}{8\pi} + \frac{\langle |E_l^2| \rangle}{4\pi} + \frac{3}{2} n^h T^h \right) + \nabla \cdot (\mathbf{I} + \mathbf{q}^h) = 0}$$



Conversion to hot!



Итоги :

$$\nabla T_e > (\nabla T)_{th} = 0.015 \frac{T_e}{\lambda_{ei}} \sqrt{\frac{Z}{A}}, \quad Z \gg 1$$

NIF, Direct drive
PRL **120**, 055001 (2018)

$$T_e = 4.5 \pm 0.2 \text{ keV}$$

hohlraum gold wall plasma or direct ablated plasma from gold target

$T_e \simeq 1 \text{ keV}$, $Z \simeq 50$, and $n_e \simeq 10^{21} \text{ cm}^{-3}$ the threshold gradient length, $L = |\nabla \ln T_e|^{-1}$ is $L \approx 100 \mu\text{m}$

it is likely that in a gold plasma corona, IAT is in regime of considerable anisotropy, $K_N \ll 1$

$$A = 1 - \exp(-d)$$

$$d \simeq 1.2 \times 10^{-2} \left(\frac{n_e}{n_c}\right)^{3/2} \sqrt{\frac{Z^3 T_e L}{A T_i \lambda}} \left[\frac{\cos^2 \phi_0}{1 + \ln 1/K_N} + 0.6 K_N \sin^2 \phi_0 \right], \quad (K_N < 1)$$

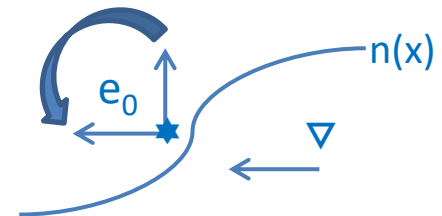
$$d \sim 10^{-2} \frac{L}{\lambda} \left[\frac{\cos^2 \phi_0}{1 + \ln 1/K_N} + 0.6 K_N \sin^2 \phi_0 \right] \quad \text{Nd:Yag laser } (\lambda = 355 \text{ nm}): d \sim 1, L \sim 100 \mu\text{m}$$

Экспериментальная идентификация :

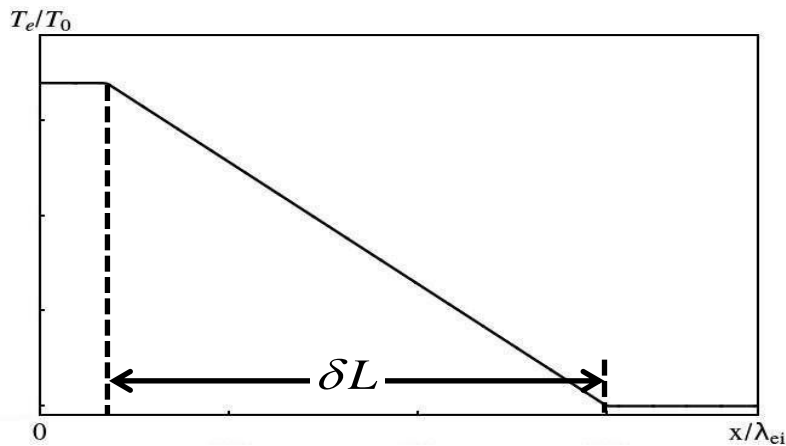
1. Проверка порогового условия (Томсоновская диагностика)
2. Более сильное поглощение р-поляризованного света по сравнению с s-поляризованным
3. При резонансном поглощении появляются быстрые электроны (как при лин. трансф.)
4. Корреляция между аномальным поглощением и подавлением теплопереноса
5. Прямое измерение усиленных шумов томсоновским рассеянием (ср. Gray, Kilkenny, 1980)
6. Регистрация значительного диффузного рассеяния
7. Прямое измерение поглощения, например, в эксперименте с лазерным пучком поперек градиента неоднородности.

Изменение поглощения при повороте вектора поляризации.

8. Корреляция горячих электронов и аномального поглощения.



ЭЛЕКТРОННЫЙ ТЕПЛОПЕРЕНОС В ГОРЯЧЕЙ ПЛАЗМЕ



$$\delta_T = \lambda_{ei} \frac{d \ln T_e}{dx}$$

Основные параметры задачи:

T_e/T_0 - электронная температура

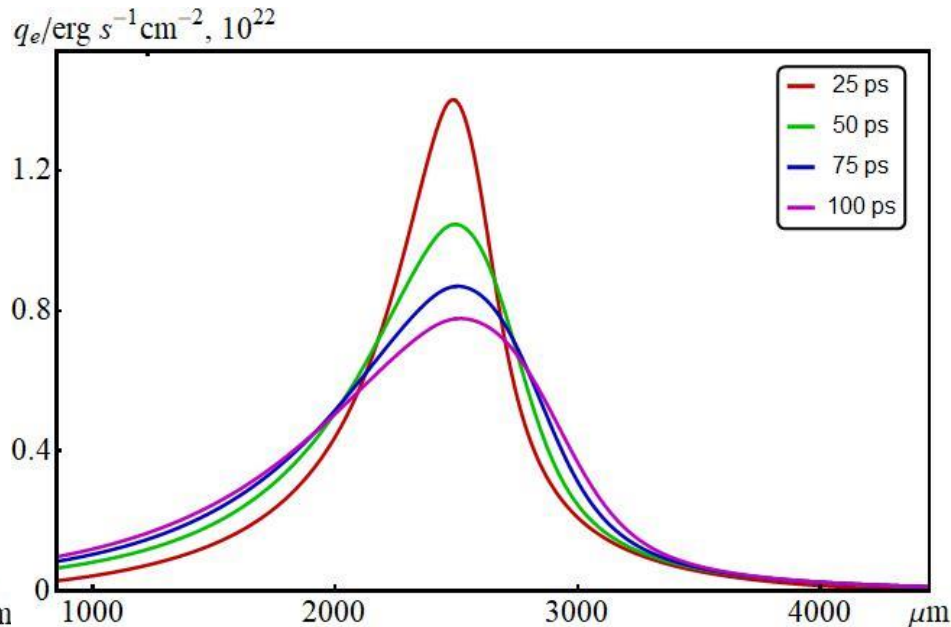
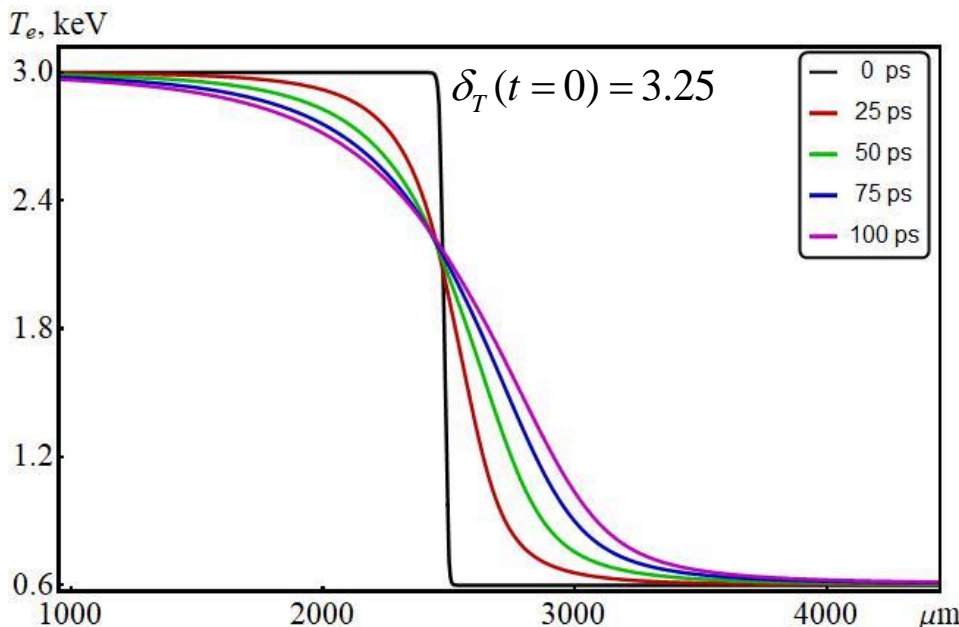
n_e/n_0 - плотность числа электронов

δ_T - характерный масштаб изменения температуры в два раза

Z - заряд ионов

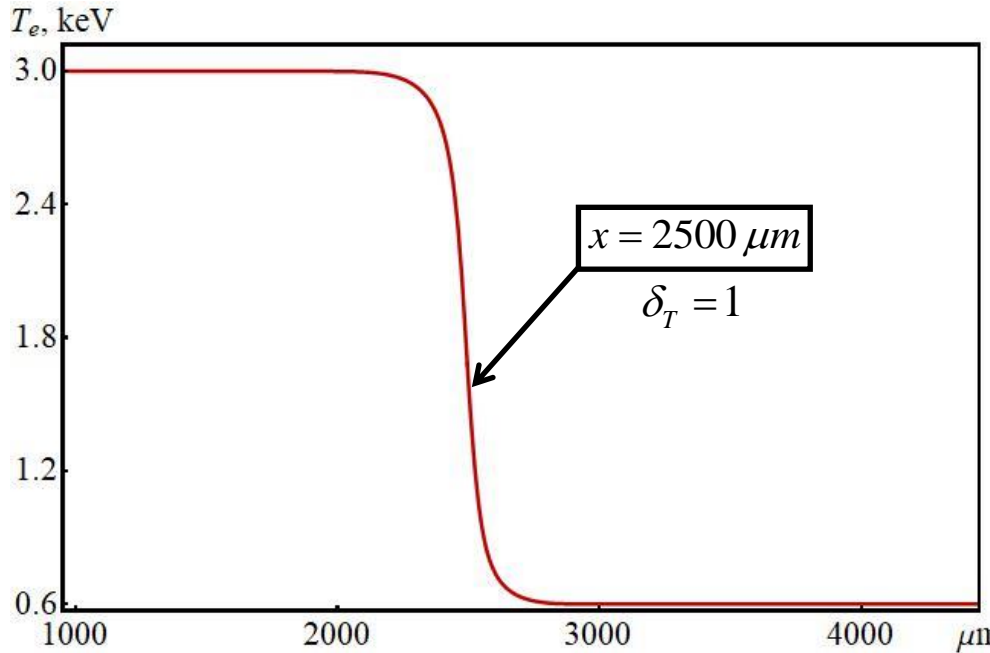
$$\lambda_{ei}(T_0, n_0) = \frac{3}{4\sqrt{2\pi}} \frac{T_0^2}{Ze^4 n_0 \Lambda_{ei}}$$

Для плазмы с параметрами: $T_0 = 3.0 \text{ keV}$, $n_0 = 10^{21} \text{ cm}^{-3}$, $Z = 1$, $\delta L = 40 \mu\text{m}$, $\lambda_{ei}(T_0, n_0) = 128 \mu\text{m}$

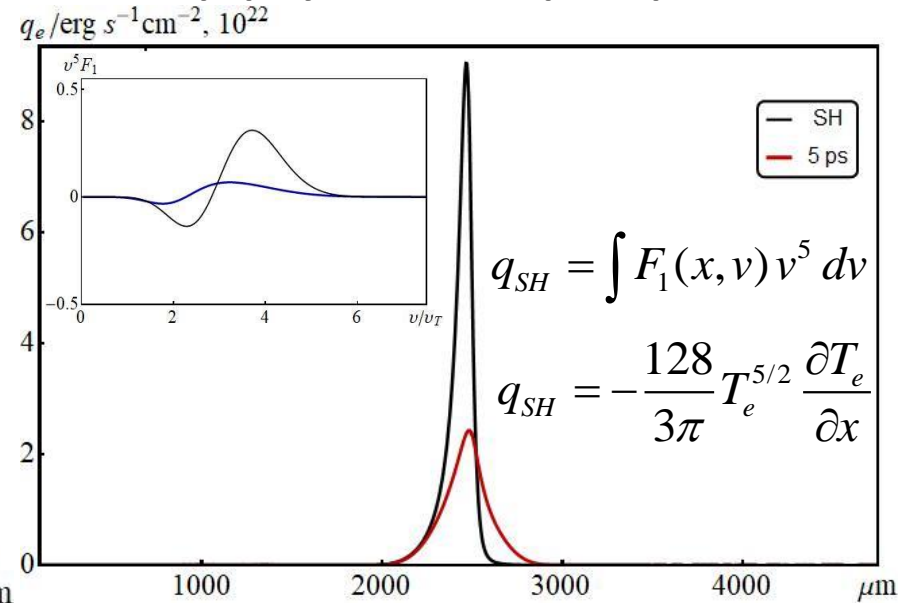


ЭЛЕКТРОННЫЙ ТЕПЛОПЕРЕНОС В ГОРЯЧЕЙ ПЛАЗМЕ

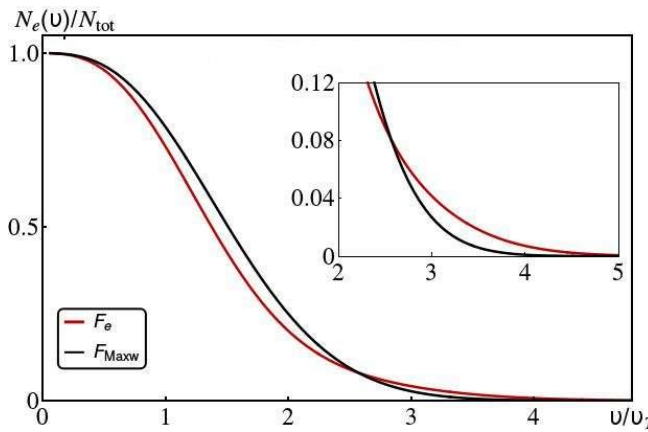
Момент времени $t = 5 \text{ ps}$



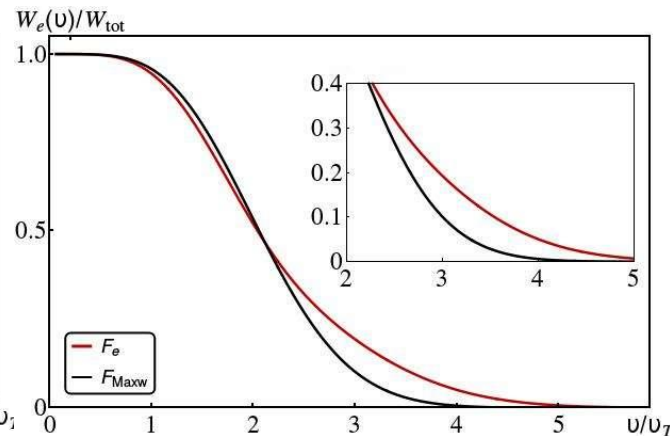
Сравнение теплового потока с формулой Спитцера-Харма:



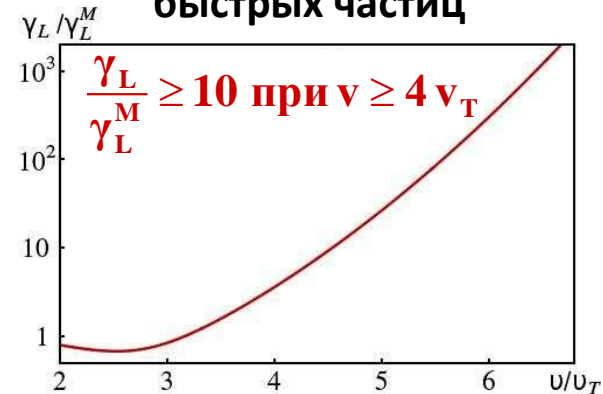
Доля горячих электронов
(для $v \geq 3 v_T$) составляет **4%**



Вклад горячих электронов
в среднюю энергию \approx **20%**

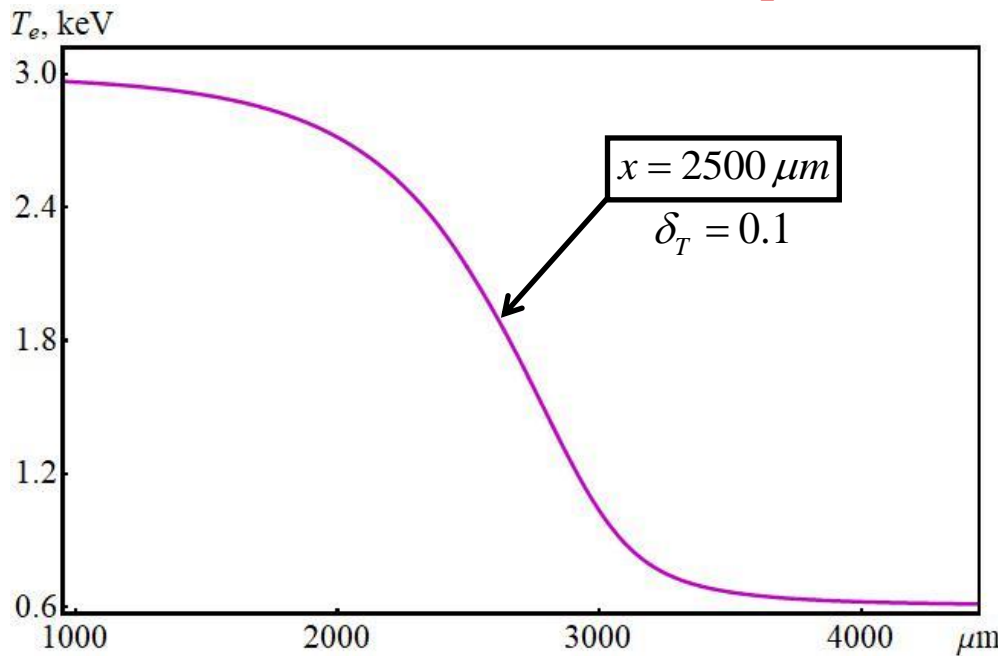


Изменение коэффициента
затухания Ландау для
быстрых частиц

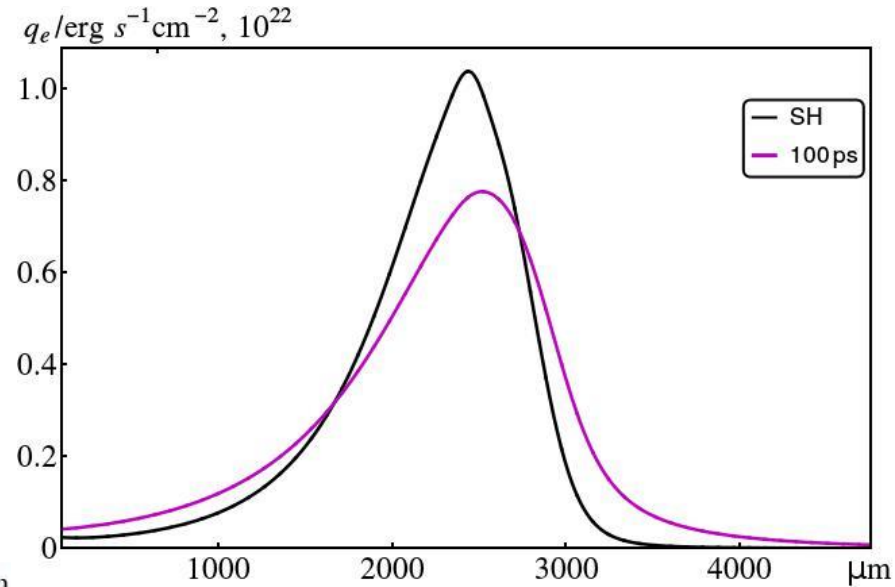


ЭЛЕКТРОННЫЙ ТЕПЛОПЕРЕНОС В ГОРЯЧЕЙ ПЛАЗМЕ

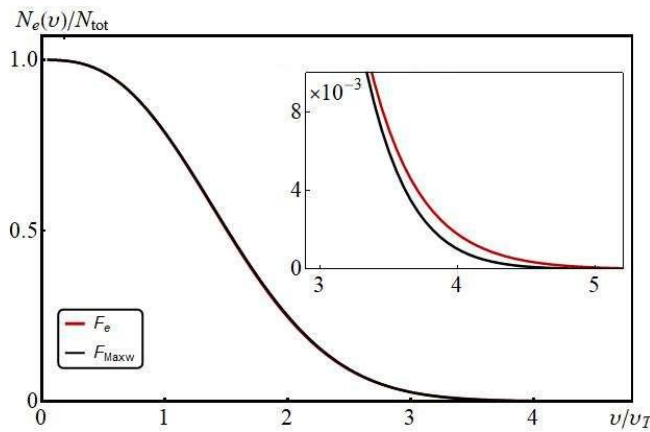
Момент времени $t = 100 \text{ ps}$



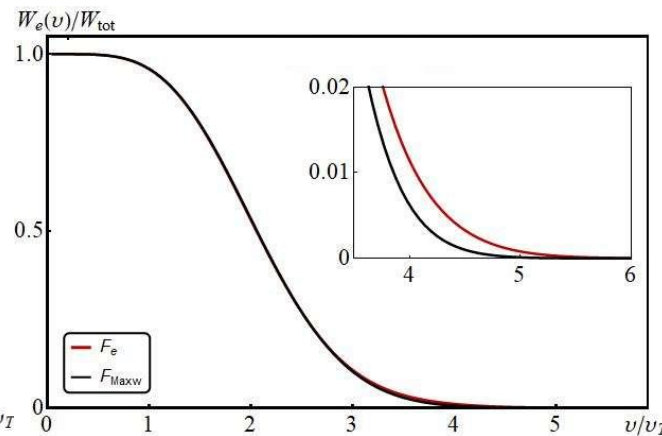
Сравнение теплового потока с формулой Спитцера-Харма:



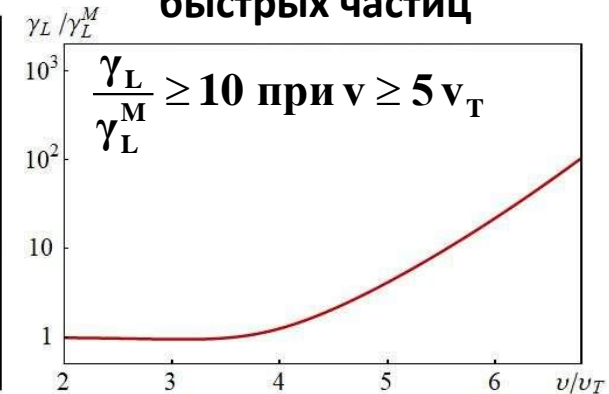
Доля горячих электронов (для $v \geq 3 v_T$) составляет **0.1%**



Вклад горячих электронов в среднюю энергию $\approx 2\%$

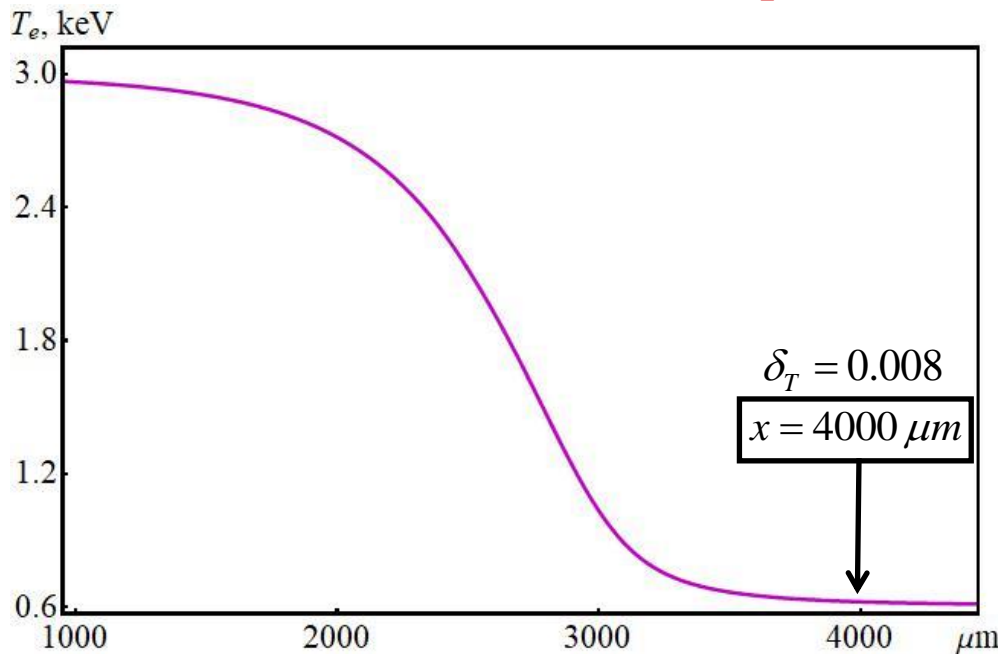


Изменение коэффициента затухания Ландау для быстрых частиц

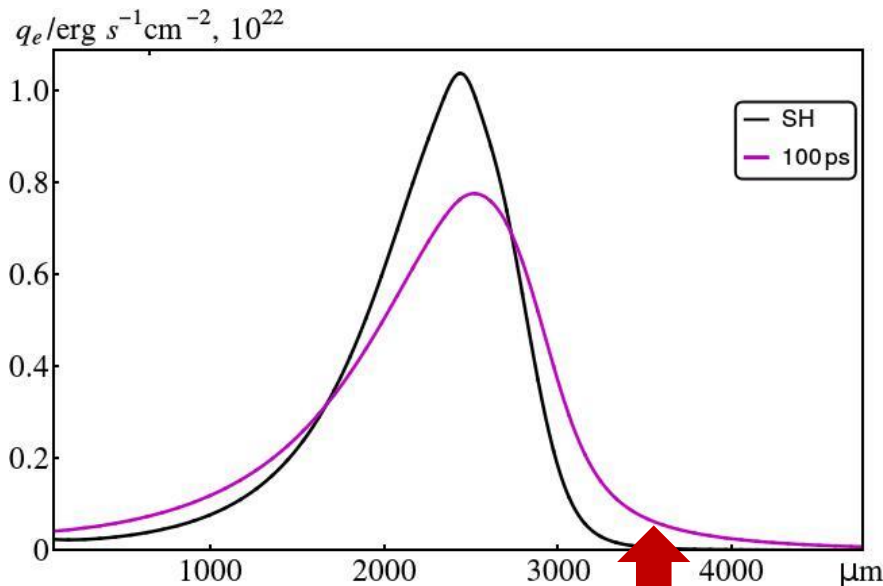


ЭЛЕКТРОННЫЙ ТЕПЛОПЕРЕНОС В ПЛАЗМЕ ЛТС

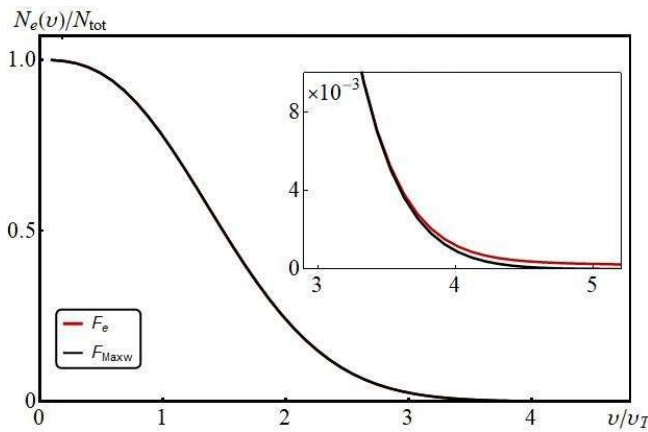
Момент времени $t = 100 \text{ ps}$



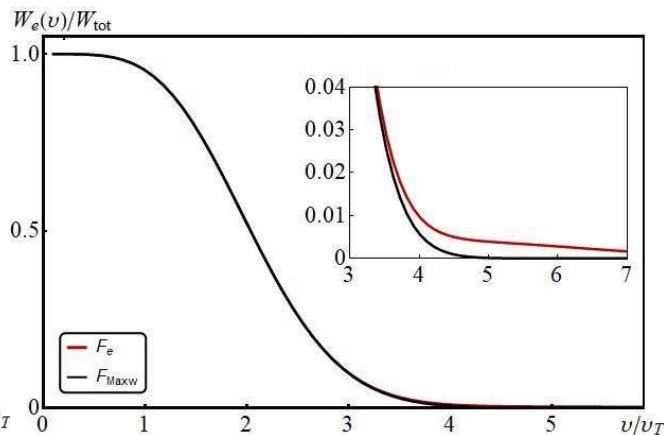
Сравнение теплового потока с формулой Спитцера-Харма:



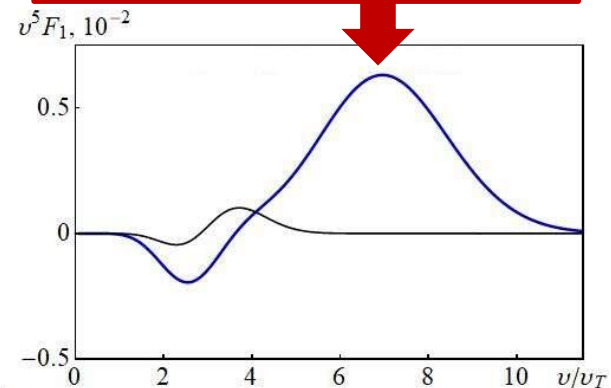
Доля горячих электронов (для $v \geq 4 v_T$) составляет 0.1%



Вклад электронов $4v_T \leq v \leq 6v_T$ в среднюю энергию $\approx 1\%$



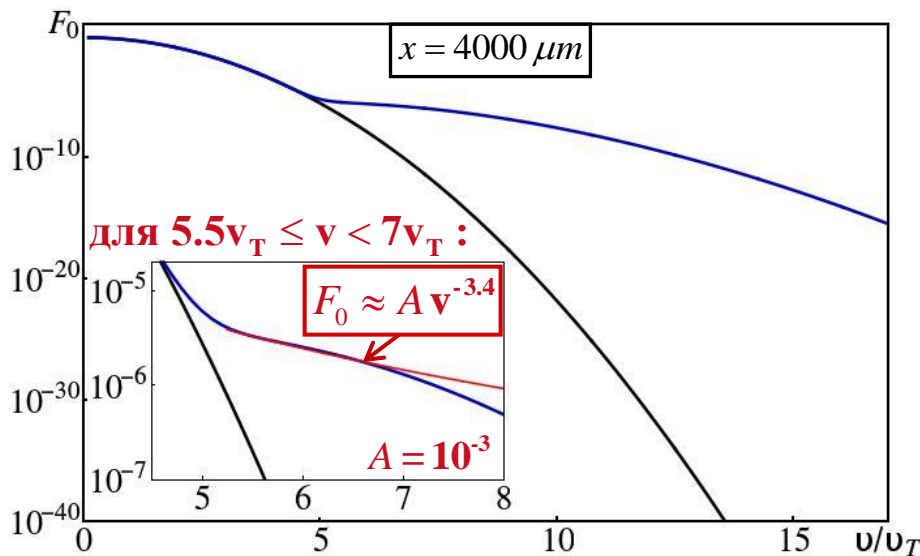
Кинетический тепловой поток много больше спитцеровского!



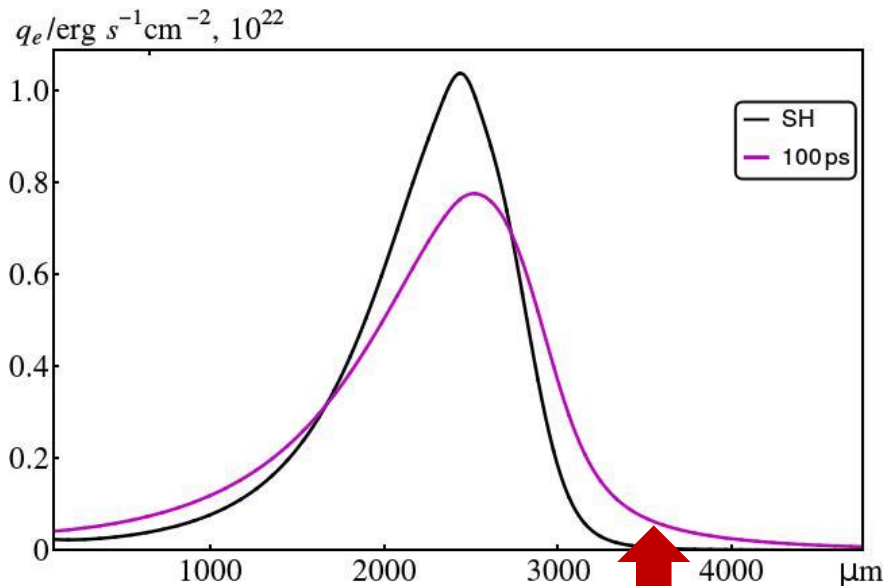
ЭЛЕКТРОННЫЙ ТЕПЛОПЕРЕНОС В ГОРЯЧЕЙ ПЛАЗМЕ

Момент времени $t = 100 \text{ ps}$

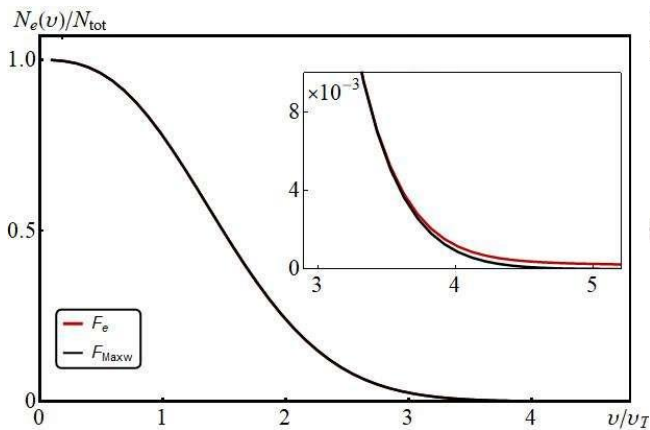
Симметричная часть электронной ФР:



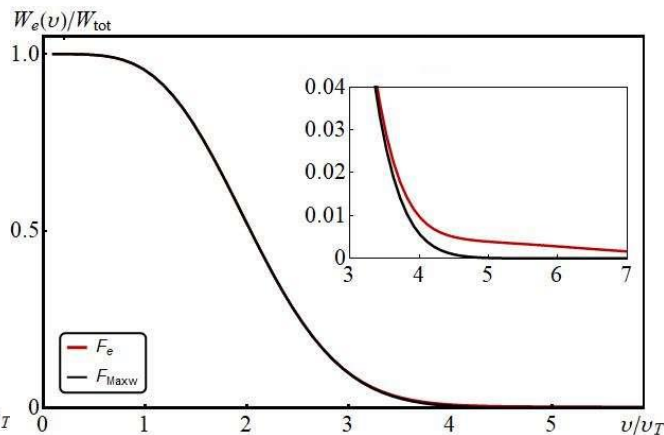
Сравнение теплового потока с формулой Спитцера-Харма:



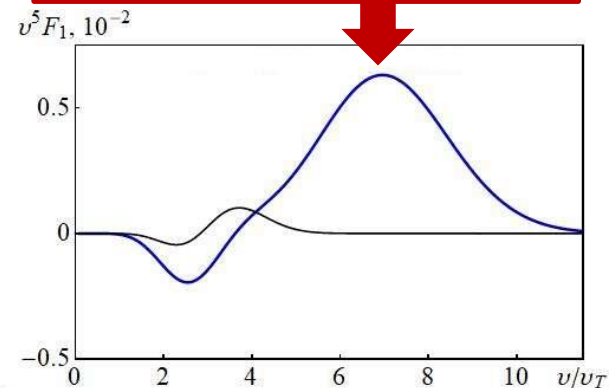
Доля горячих электронов (для $v \geq 4v_T$) составляет 0.1%



Вклад электронов $4v_T \leq v \leq 6v_T$ в среднюю энергию $\approx 1\%$

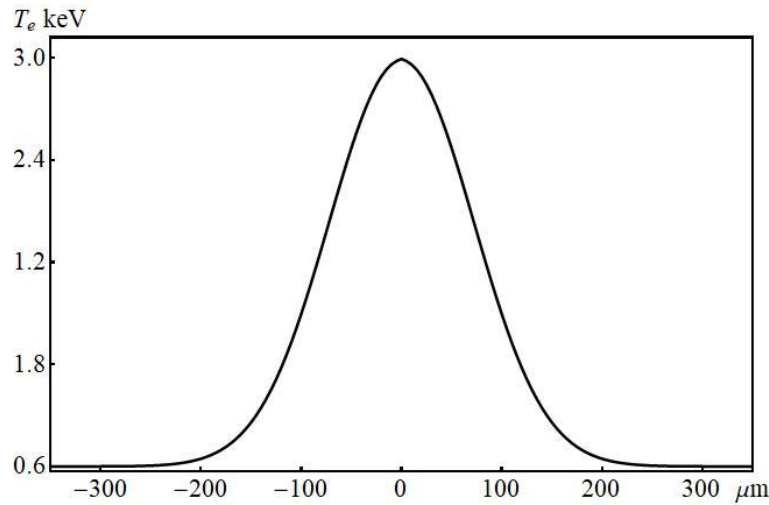


Кинетический тепловой поток много больше спитцеровского!



ЭЛЕКТРОННЫЙ ТЕПЛОПЕРЕНОС. ГОРЯЧЕЕ ПЯТНО

Начальный профиль температуры:



$$T_e(x) = T_\infty + T_C \exp\left(-\frac{x^2}{\delta L^2}\right)$$

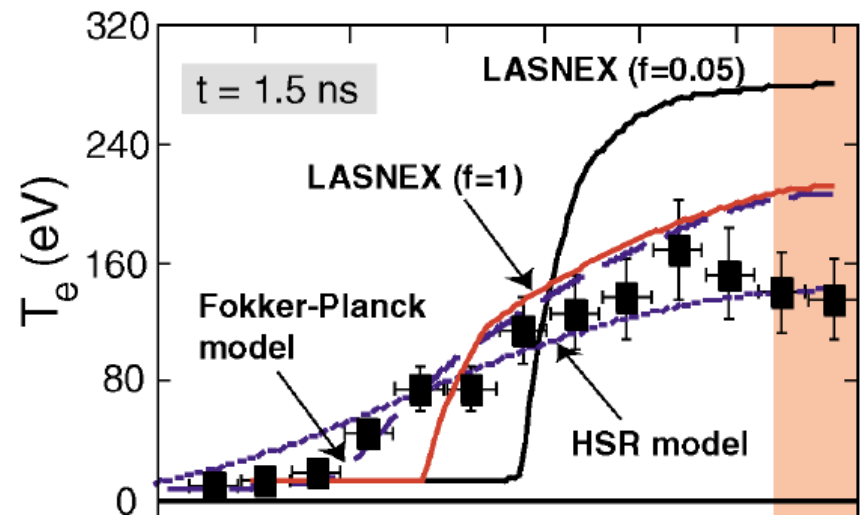
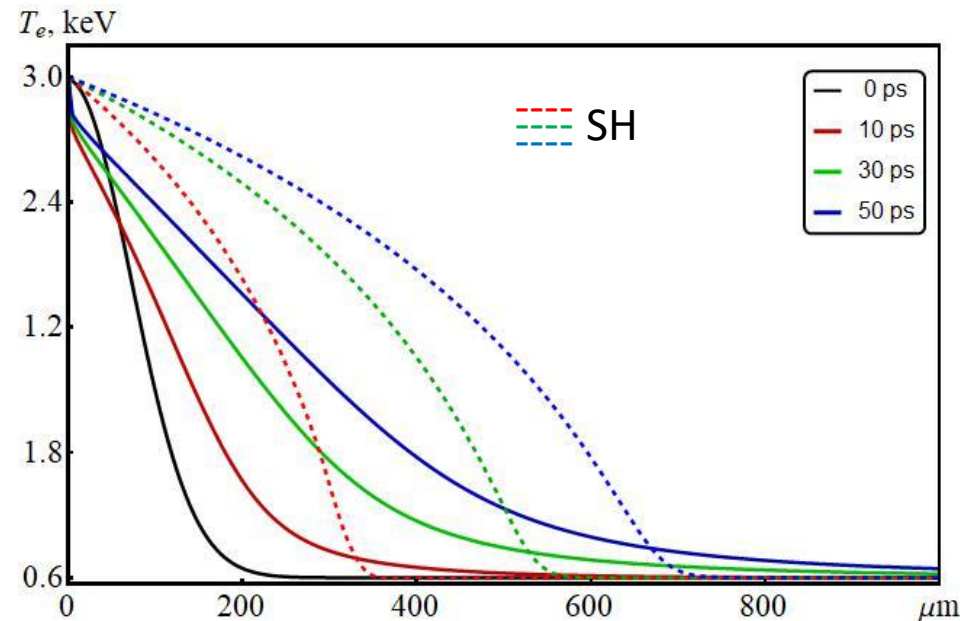
$$T_\infty = 0.2T_0, \quad T_C = 0.8T_0$$

Параметры плазмы:

$$T_0 = 3.0 \text{ keV}, n_0 = 10^{21} \text{ cm}^{-3}, Z = 1, \delta L = 100 \mu\text{m}$$

Нагрев в центре:

$$F_e(x=0, \nu) = F_M(\nu, T_0, n_0)$$



Effect of Nonlocal Transport on Heat-Wave Propagation

G.Gregori, S.Glenzer, J.Knight, C.Niemann, D.Price, D.Froula, M.Edwards, R.Town, A. Brantov, W. Rozmus, and V.Bychenkov
 Phys. Rev. Lett. 92, 205006 (2004).

Выводы

ЛТС проект вступил в фазу «горячих» (Te 3-5 keV) исследований

Без кинетики частиц и волн не обойтись

Нужны новые физические (теоретические) модели, коды и моделирование

Нужны постановки новых первопринципных экспериментов

Эксперименты должны начинаться уже сейчас

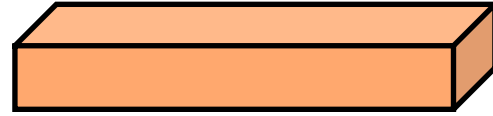
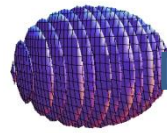
(Пример: The experiment on IAT and RCI is going to happen in Rochester at the beginning of April. It is designed in such a way that first it will repeat Glenzer's measurement on absorption and next they will look directly at IAT with Thomson scattering. Sylvie Deppiereux is going to perform this experiment.)

Примеры исследований (ФИАН, ВНИИА) по лазерной физики сверхвысоких энергий (фс)

- **Лазерно-ускоренные пучки электронов для создания плотного нагретого вещества**
- **Лазерно-ускоренные пучки электронов для глубокой гамма-радиографии**
- **Источник для фазово-контрастной микроскопии пс разрешения**
- **Лазерное ускорение ионов для инициирования ядерных реакций**

Лазерно-ускоренные пучки электронов для создания плотного нагретого вещества

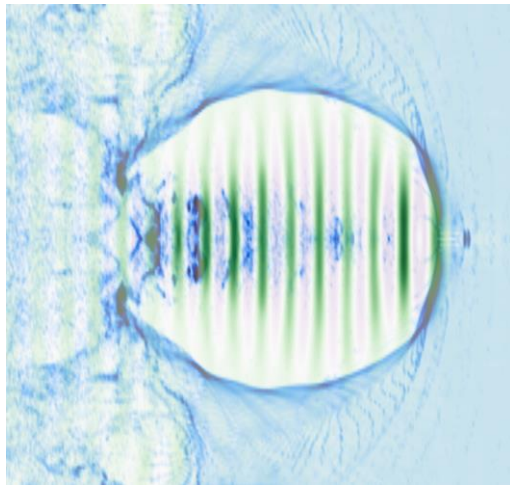
Лазерный импульс
4 Дж, 30 фс, 4 мкм



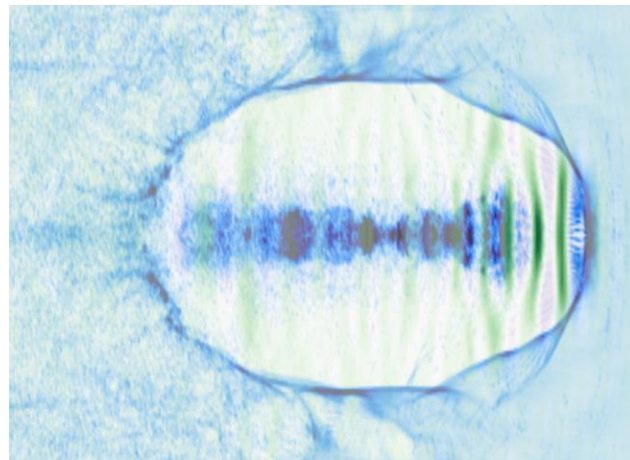
Мишень $n \sim 0.1 n_c$ 240 мкм



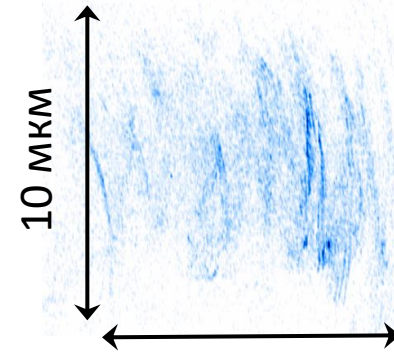
Лазерный bubble



Классический bubble

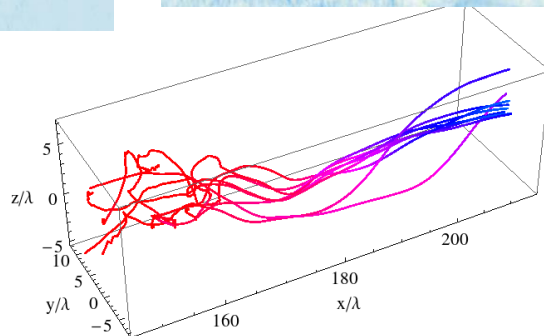


Вылетевший пучок
электронов
7 нКулон, 100 МэВ



15 мкм

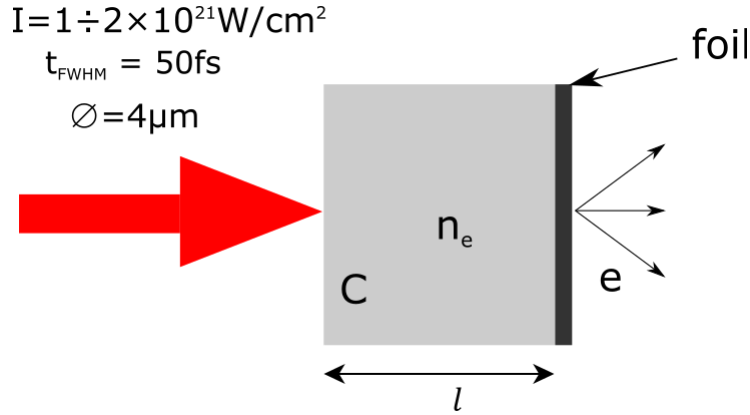
Стохастический
впрыск
электронов



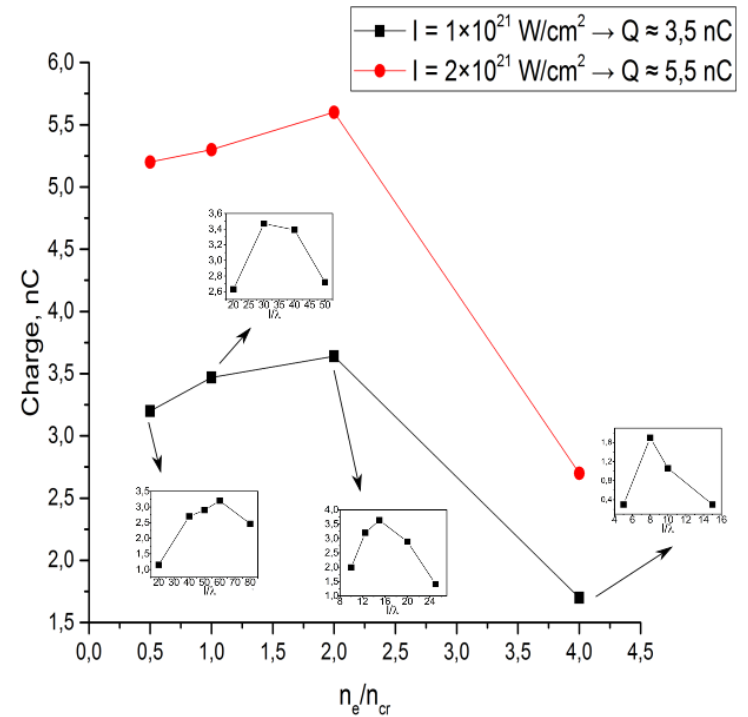
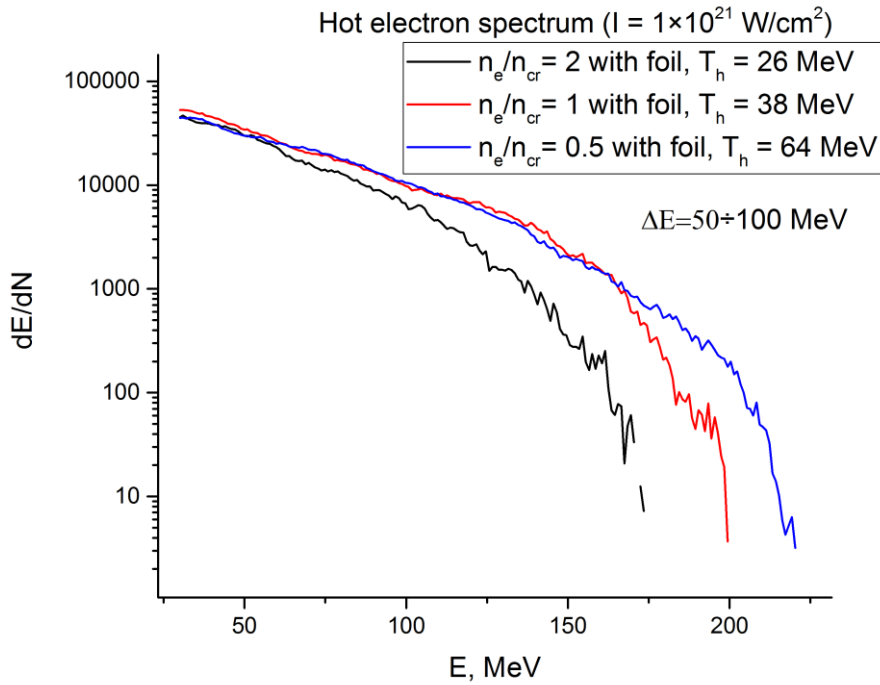
Плотность энергии 2×10^8 Дж/см³

Давление ~ 2 Гбар !

Electron acceleration from low-density targets



Electrons for deep radiography

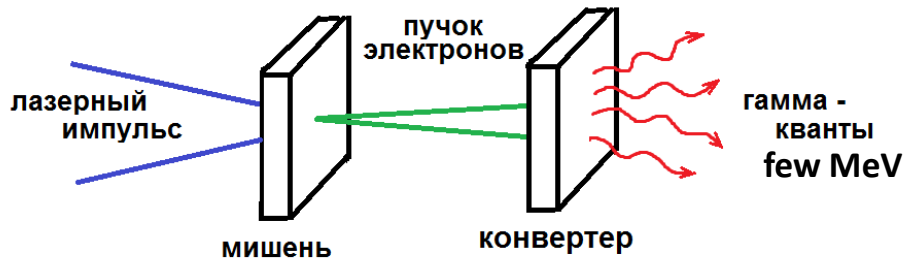
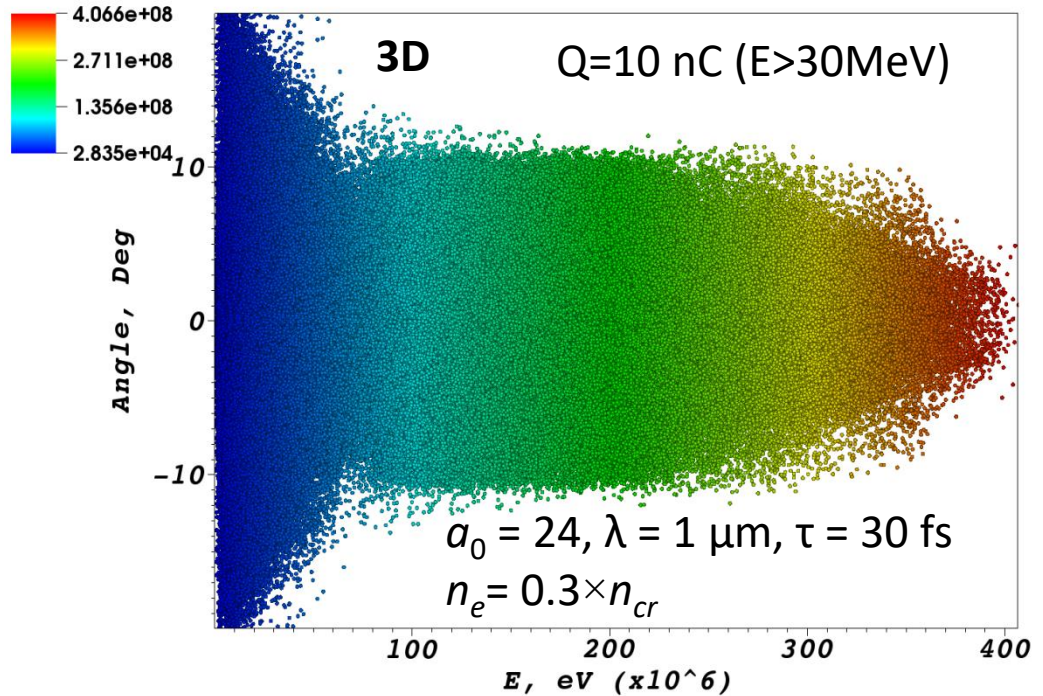


Electron acceleration and gamma emission

$$N_{\max} = ?$$

$$\epsilon_e N_{\max} \sim A E_{\text{las}}, \quad \epsilon_e = m_e c^2 a^2 / 4$$

$$N_{\max} = \frac{A E_{\text{las}}}{\epsilon_e} \Rightarrow n_e \lesssim n_c$$



Deep γ -radiography
(10-20 cm dense matter)

Single shot radiography:

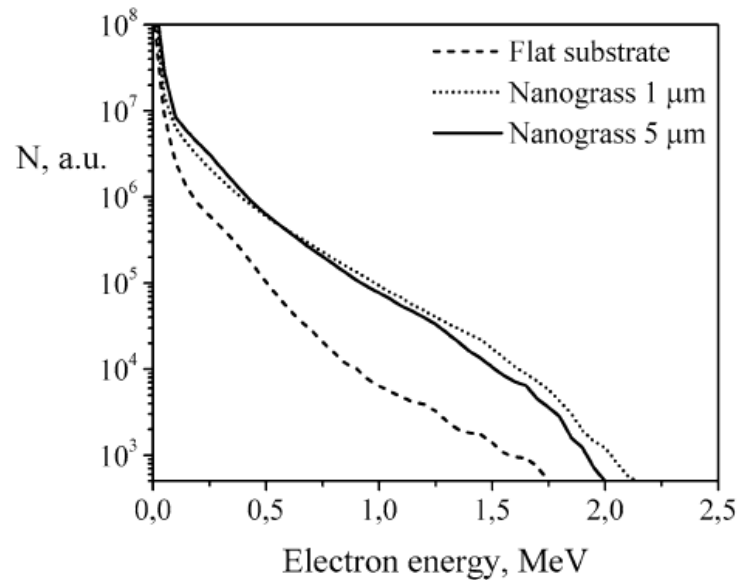
150 nQ



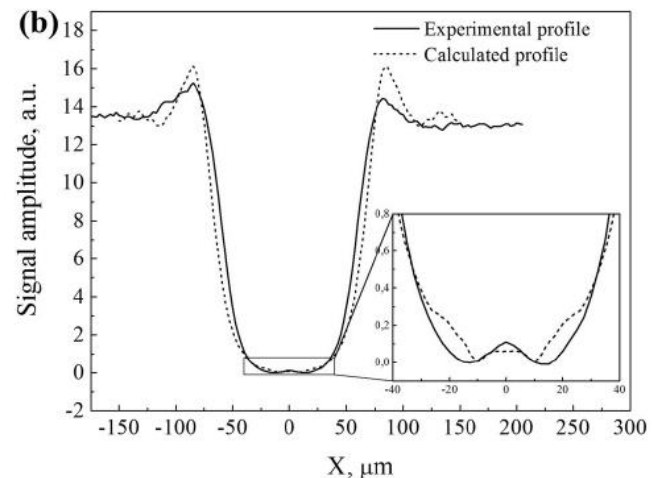
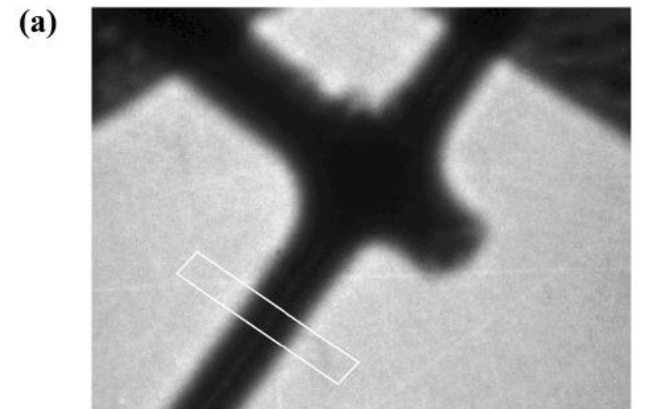
PW lasers

Фазово-контрастная микроскопия от лазерно-ускоренных электронов

Experimental results supported by 2D3V Particle-In-Cell simulations of laser–plasma interaction show that a laser-based plasma source, formed onto the surface of a solid target may be utilized for phase contrast X-ray imaging in a wide energy range of photons. [K. A. Ivanov et al., Appl. Phys. B **123**, 252 \(2017\)](#)



Electron energy spectra for flat foil and nanowires target with different rods length



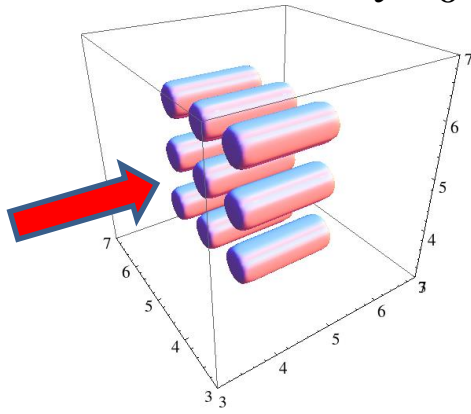
Наши исследования по лазерно-плазменной физике высоких энергий для лазерной активации

- 1) 1998-1999 гг. В.Ю. Бычковым сформулирована идея о лазерном инициировании ядерных реакций с использованием фс лазерных импульсов и даны первые теоретические оценки (ЖЭТФ **115**, 2080, 1999);
- 2) 1999-2001 гг. Коллаборация с Университетом Мичигана по лазерному получению медицинских изотопов. Эксперименты по получению радиоактивного ^{11}C (Appl. Phys. Lett. 78, 595, 2001, SPIE Proc. **4424**, 553, 2001);
- 3) 2001 г. В коллаборации с Университетом Осаки, предложение и расчет лазерного получения пионов при генерации протонов (Письма в ЖЭТФ **74**, 664, 2001);
- 4) 2014-2015 гг. Оптимизационные расчеты по лазерной наработке изотопов для ПЭТ, ОФЭКТ и нейтронов медицинского применения из тонких мишеней (Laser & Particle Beams **32**, 605, 2014, УФН **185**, 77, 2015, Eur. Phys. J. **224**, 2621, 2015);
- 5) Н/Р Расчет лазерных источников нейтронов и разнообразных изотопов на основе пакета 3D Vsim - GEANT 4 из различных мишеней, включая низкоплотные и микро-структурированные с большим объемным нагревом. Направленный источник нейтронов (p-n реакции налету) и источник термоядерных нейтронов (dd, dt).

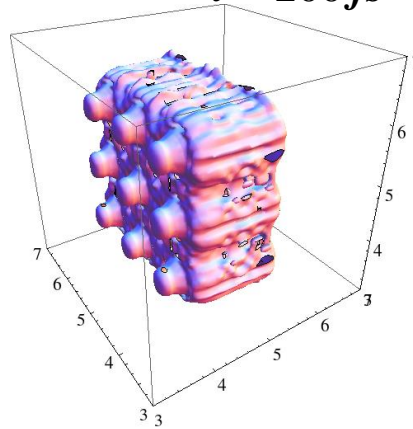
Генерация DD и DT нейтронов

$$r_0 = 0.15 \mu\text{m}, \quad H = 1 \mu\text{m}$$

$$t = 0$$

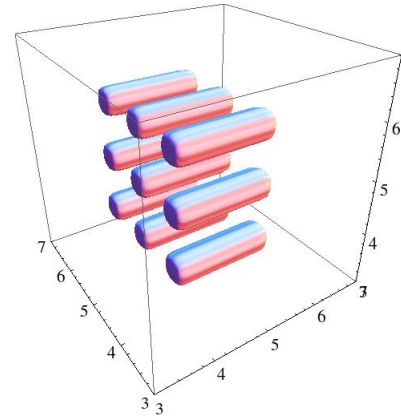


$$t = 200 \text{ fs}$$

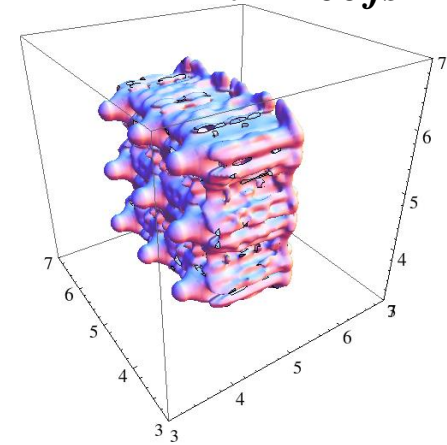


$$r_0 = 0.2 \mu\text{m}, \quad H = 1 \mu\text{m}$$

$$t = 0$$

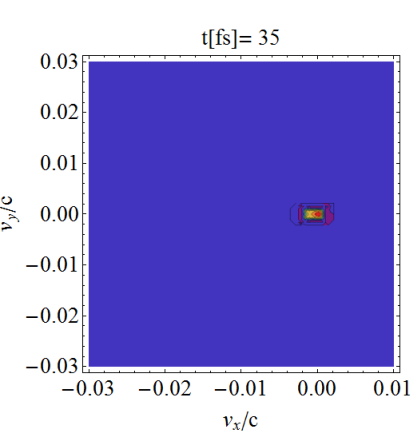


$$t = 200 \text{ fs}$$

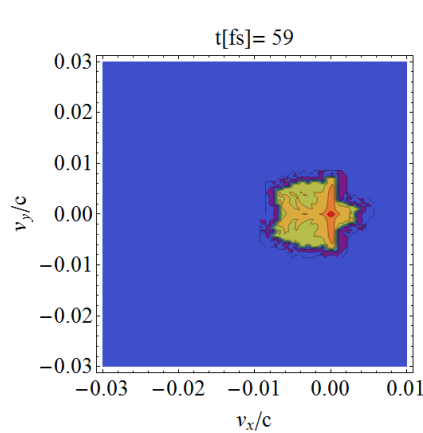


Ion distribution $d^2N/dv_x dv_y$

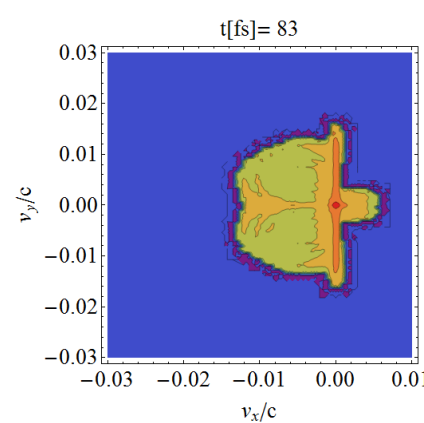
$$t = 35 \text{ fs}$$



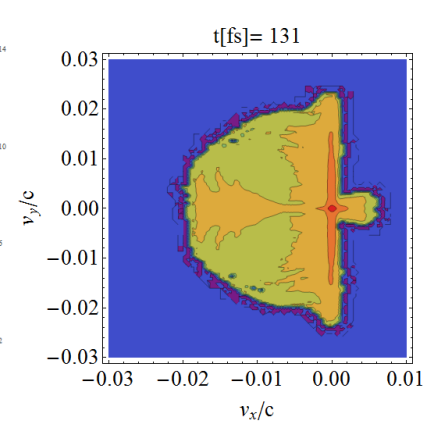
$$t = 59 \text{ fs}$$



$$t = 83 \text{ fs}$$

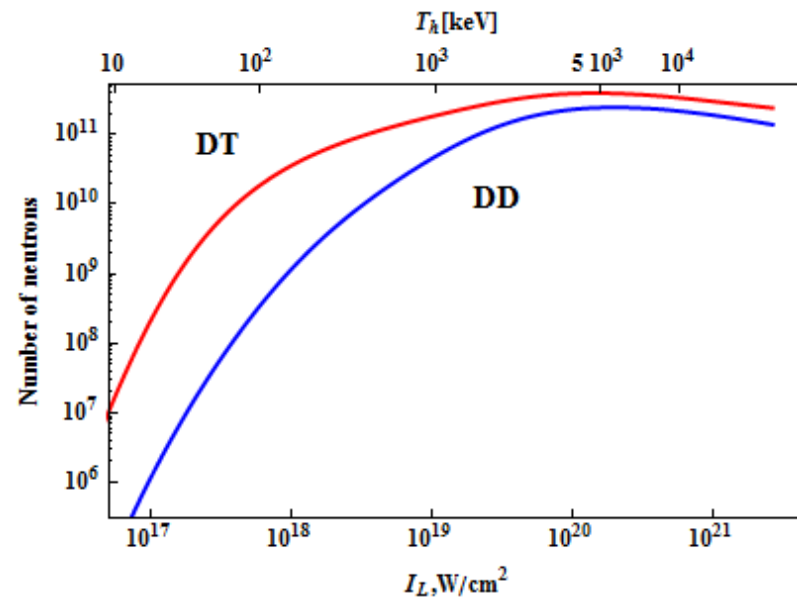
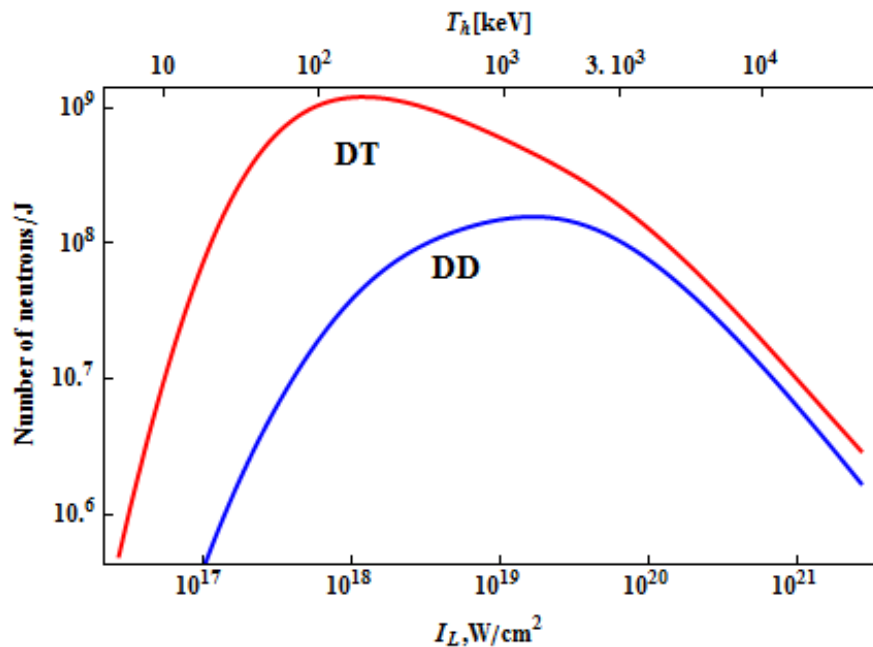


$$t = 131 \text{ fs}$$



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.

Выход нейтронов (на 1 J)



1PW laser pulse, $I_L=10^{18}$ W/cm², $\lambda_L = 0.8$ μ m, $L = 5$ μ m (length of wires)

Number of pins in focal spot $\approx 10^5$, yield from one pin $Y_0 \approx 10^4 \rightarrow N_N \approx N_{\text{pin}} \cdot Y_0 \approx 10^{10}$

Yield DD\Power	1PW	10PW
	up to 10^9 ($3 \cdot 10^7$ /J)	up to 10^{10} ($3 \cdot 10^7$ /J)

Ведутся расчеты реакций налету (p,n) для получения направленных потоков нейтронов

Выводы

- Возможна практическая реализация фазово-контрастного имиджинга с разрешающей способностью микронного пространственного и суб-пикосекундного временного масштабов на лазерах мульти-ТВт уровня
- Переход к ПВт лазерам может позволить создать практический источник для глубокой гамма-радиографии
- При оптимизированной схеме облучения, лазеры в сотни ТВт способны обеспечить Гига-барные давления
- Имеются перспективы получения направленных потоков нейтронов практического интереса на ПВт уровне мощности лазера