“Hot” electron currents in ultra-intense laser-solid interactions

Thomas Kluge

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Partially supported by EC FP7 LASERLAB-EUROPE/CHARPAC (contract 284464) and German Federal Ministry of Education and Research (BMBF) (contract 03Z1O511).

DRACO: 500 TW, 30 fs Ti:Sa laser, two beam option

PeNELOPE: diode pumped PW laser (in development)

Electron acceleration, Thomson scattering, TWTS

Ion acceleration, laser-solid interaction | Ion therapy

T. E. Cowan
U. Schramm
R. Sauerbrey
M. Bussmann
K. Zeil,
J. Metzkes,
L. Huang
...

Laser particle acceleration at HZDR

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HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Partially supported by EC FP7 LASERLAB-EUROPE/CHARPAC (contract 284464) and German Federal Ministry of Education and Research (BMBF) (contract 03Z1O511).

Why are we interested in electron currents?

- self generated **magnetic fields** for guiding/divergence control

  e.g. Leblanc, Sentoku PRE **89** 023109 (2014)
- TNSA
- diagnostics
- bulk heating, e.g. L. Huang et al. POP **20** 093109 (2013)

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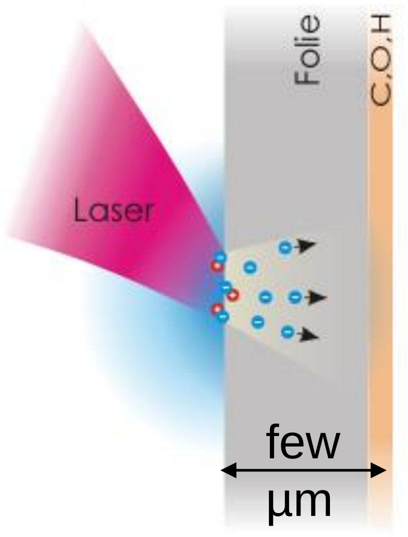
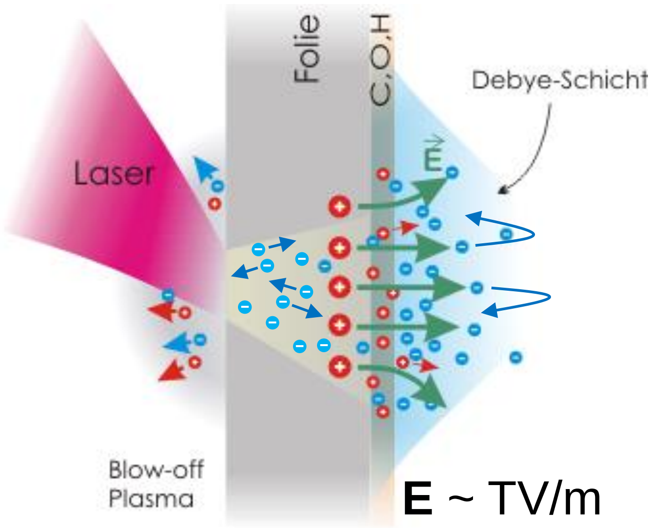
t.kluge@hzdr.de

Idealized setup

absorption and electron acceleration



electron transport, creation of Debye sheath, recirculation



accelerated electrons: density n, temperature T

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Why often Maxwellian-like distributions are observed

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10 MARCH 1980

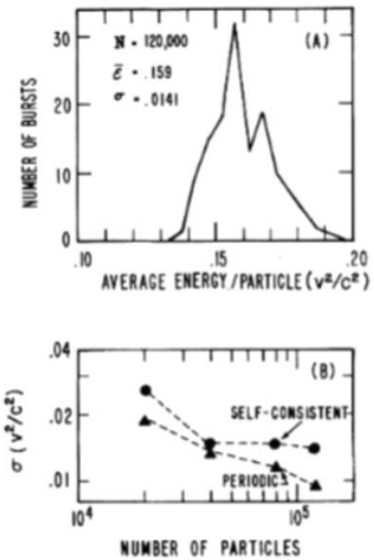


FIG. 4. (a) Pulse-height analysis of Fig. 3(b) data. Number of pulses vs pulse height. (b) Standard deviation of data from (a) vs number of simulation particles for self-consistent simulati... ticle calculations.

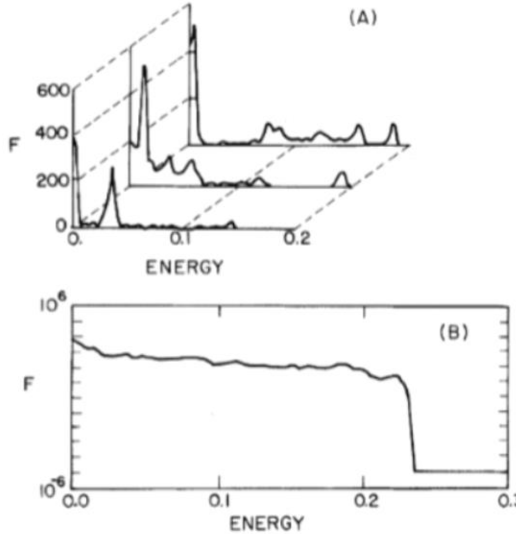


FIG. 5. Hot-electron distributions due to an injected beam with velocity $v/c = -0.08$. (a) Distributions

The ger... sity laser... the last f...

...ree modes of

tion should be compared... particle approach in whi... randomly from the ther... steady injection remove... ness and allows a syste... ing characteristics of th... collected, after passing... gion, at a spatial point... ing region to avoid colle... originating from a later... can construct a distribu... a given beam velocity c... ing cycle. This allows u... by-cycle composition of... tribution function.

In Fig. 5 we show (a) the distribution of hot par-

each weighted by the initial Maxwellian. From this result it is tempting to speculate that the Maxwellian character of the hot-electron distribution observed in self-consistent simulations of resonant absorption is directly related to the random fluctuations in the distribution of hot particles produced from cycle to cycle. Certainly, without this element of randomness, it would be very difficult to understand this observation.

excitations are self-consistently related to the

Picosecond pulses vs. few-femtosecond pulses

picosecond pulses

- expansion
- preplasma generagtion
- bulk heating
- recirculation

⇩

- relativistic oscillation of critical density surface
- electrons enter laser wave with different initial velocities in different phases

→ **randomization**

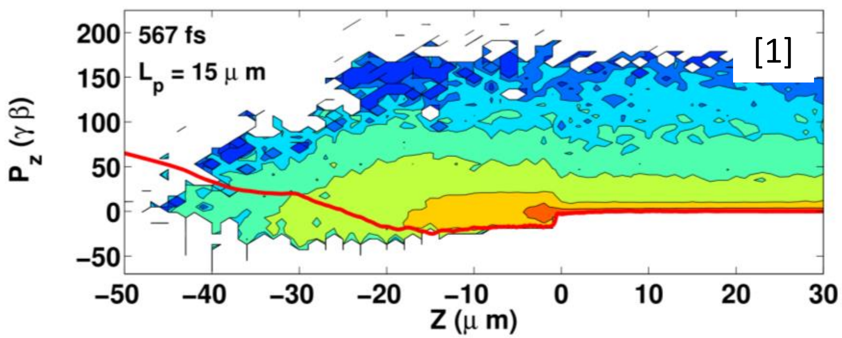
few-femtosecond pulses

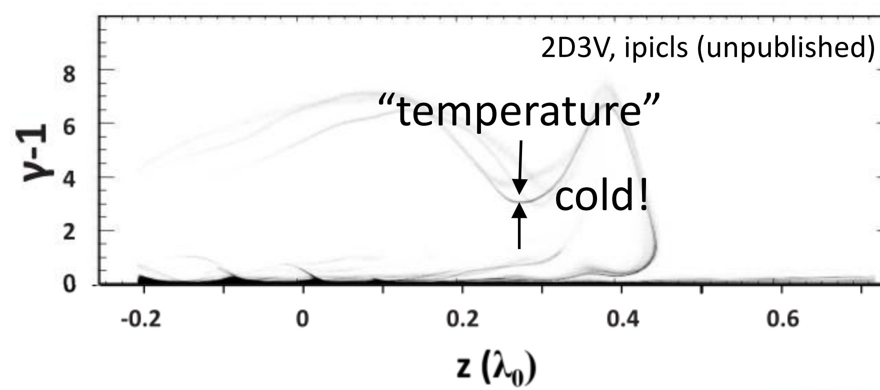
- flat target remains virtually flat
- only few 10s of nm preplasma
- no significant bulk heating
- no recirculation

⇩

- electrons enter laser wave at rest

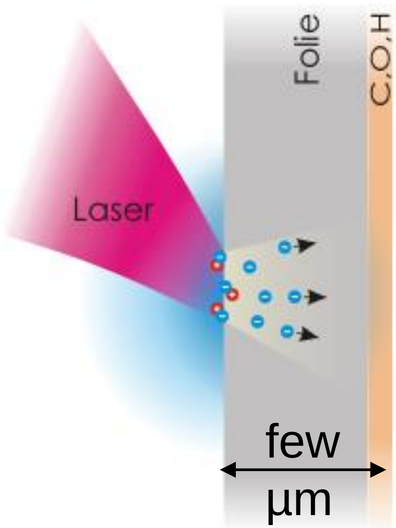
→ problem is fully **deterministic**





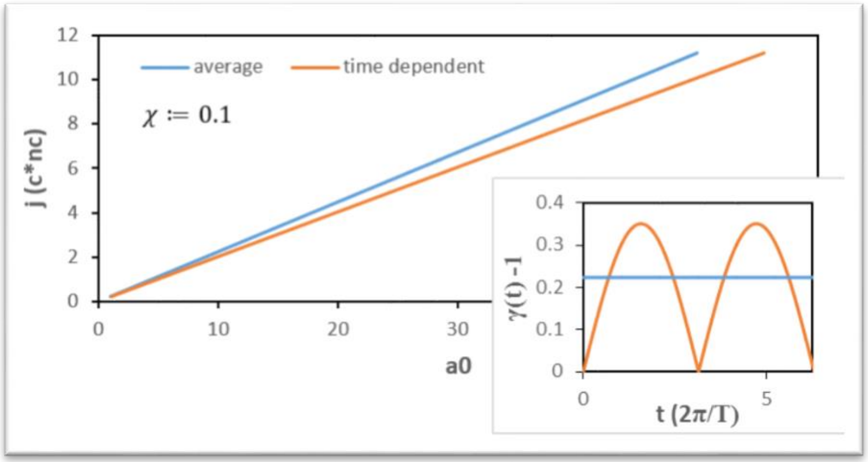
[1] B.S. Paradkar, Thesis "The effects of pre-formed plasma on the generation and transport of fast electrons in relativistic laser-solid interactions", University of California (2012)

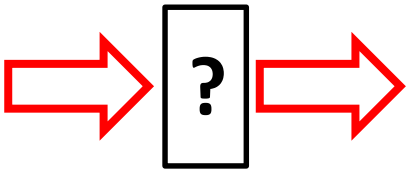
Energy flux conservation for long pulses laser pulses



assuming $p_z = \gamma_h - 1$
and $\gamma_h \cong \frac{\chi a_0}{\sqrt{2}} + 1$

$\Rightarrow$ $\boldsymbol{j_h = n_{e,hot} v_z \cong \gamma_h n_c c}$



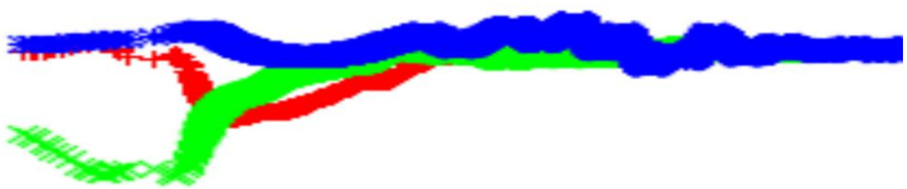


absorbed energy (per unit area and time)
χI

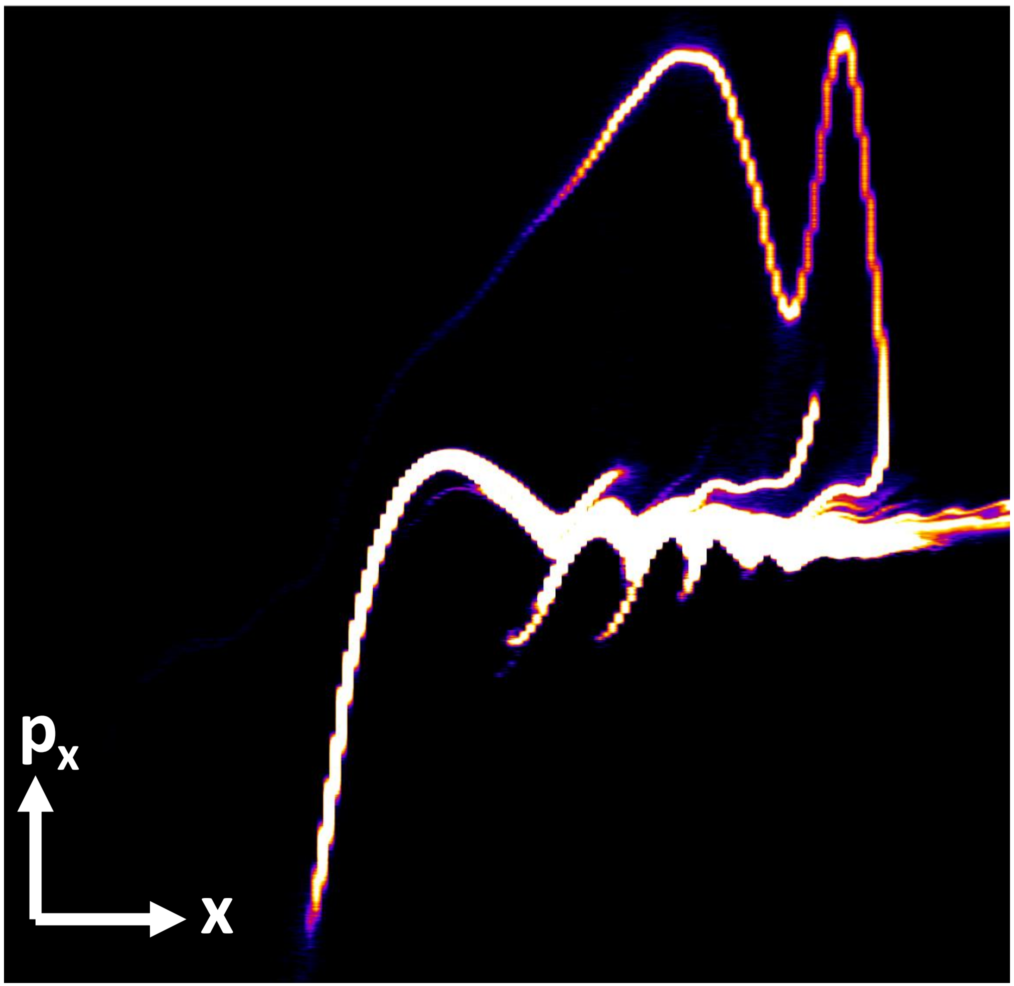
energy carried away by electrons
$n_{e,hot}(\gamma_h - 1) m_e v_z$

Haines et al., PRL **102**, 45008 (2009)
P. Leblanc, Y. Sentoku, PRE **89** 023109 (2014)

Short laser pulse (first period)



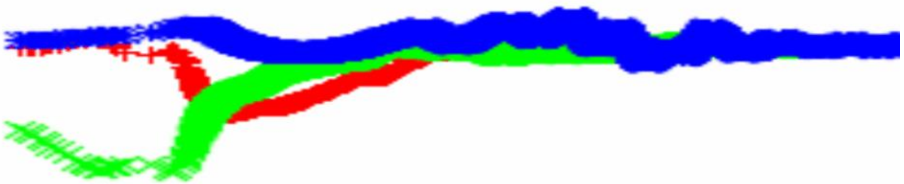
blue: Ex
green: Ey
red: Bz



PIC simulations

- ipicls2d (Y. Sentoku)
- plane laser, no ramp-up of intensity
- plane target, 400 n_c
- fully ionized, Q/A = 1/2
- small preplasma, scale length 1 micron
- a_0=1…60

Short laser pulse (first period)



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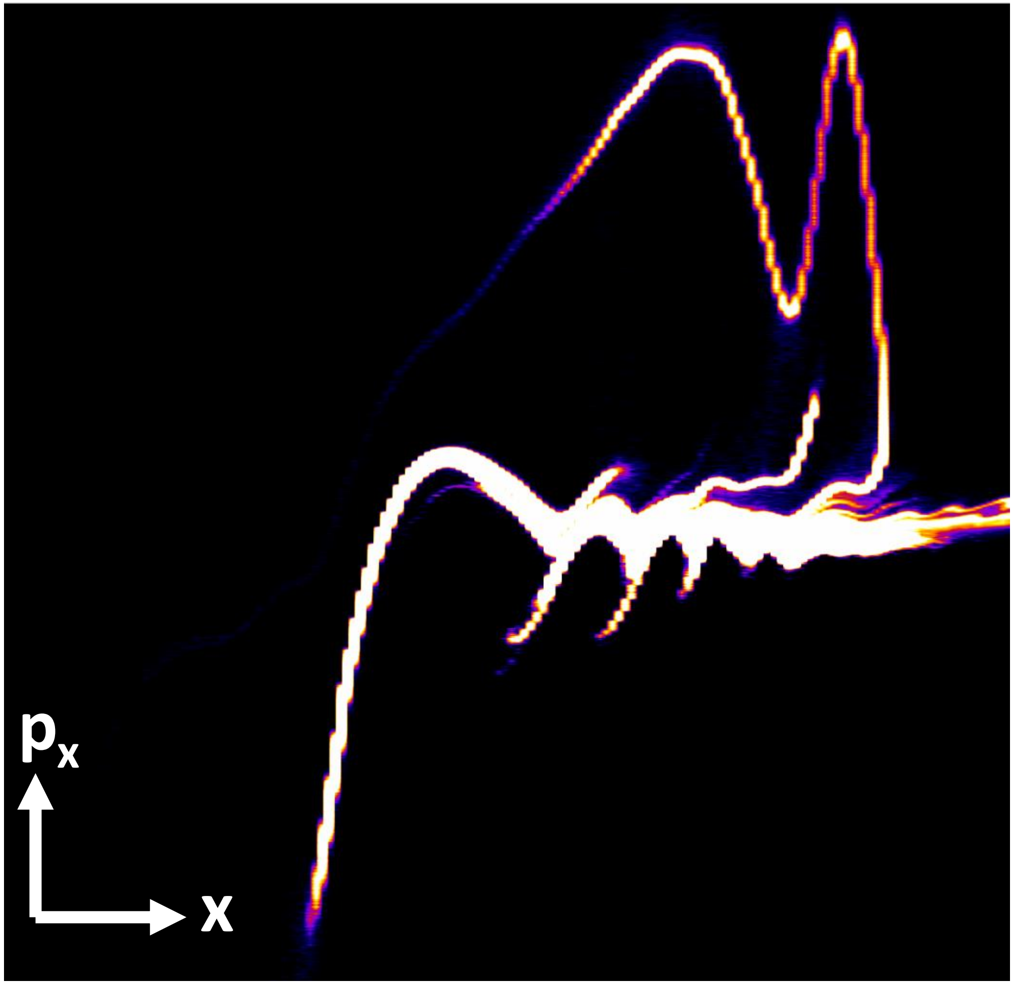

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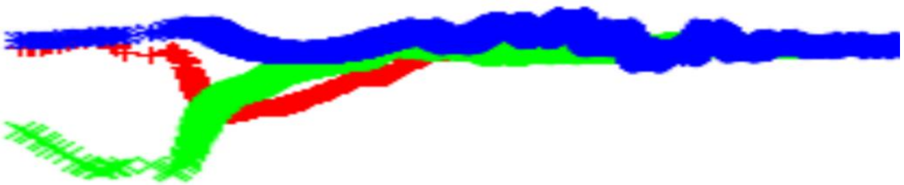
t.kluge@hzdr.de

Short laser pulse (first period)



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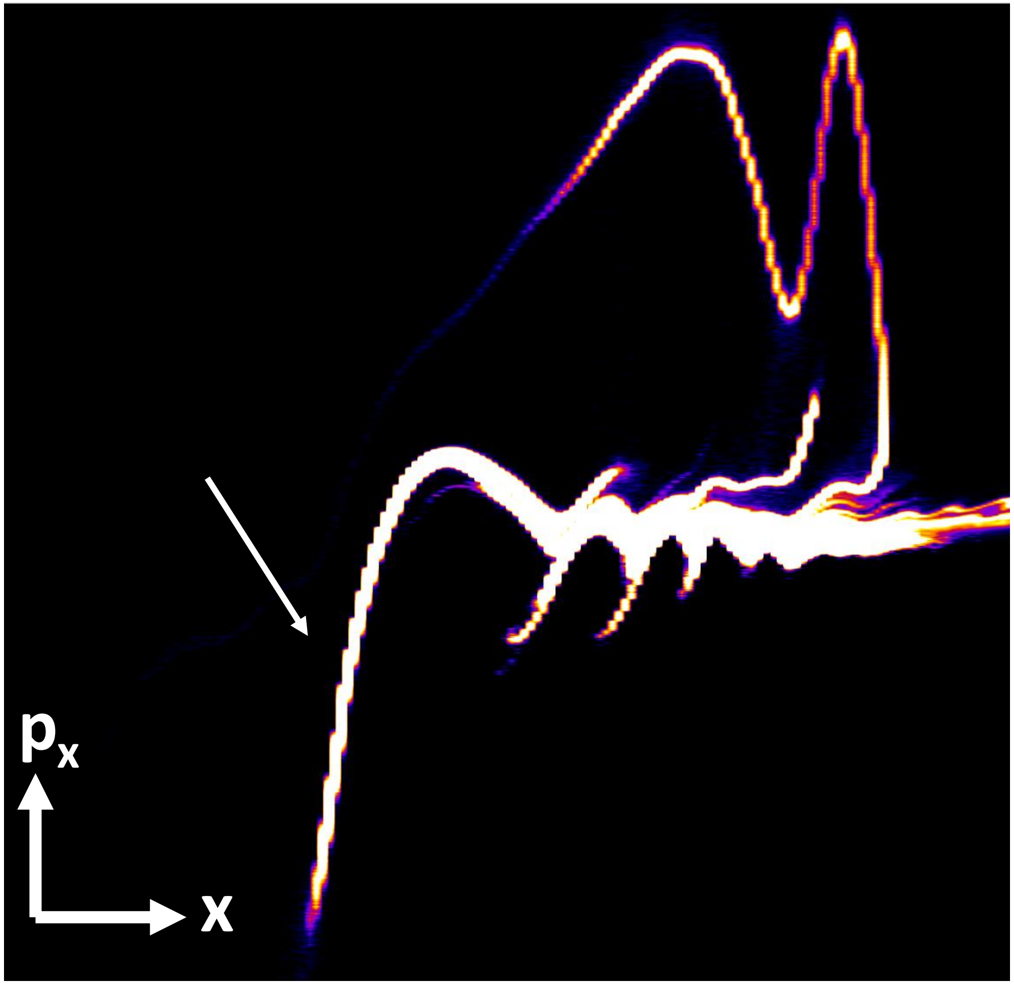
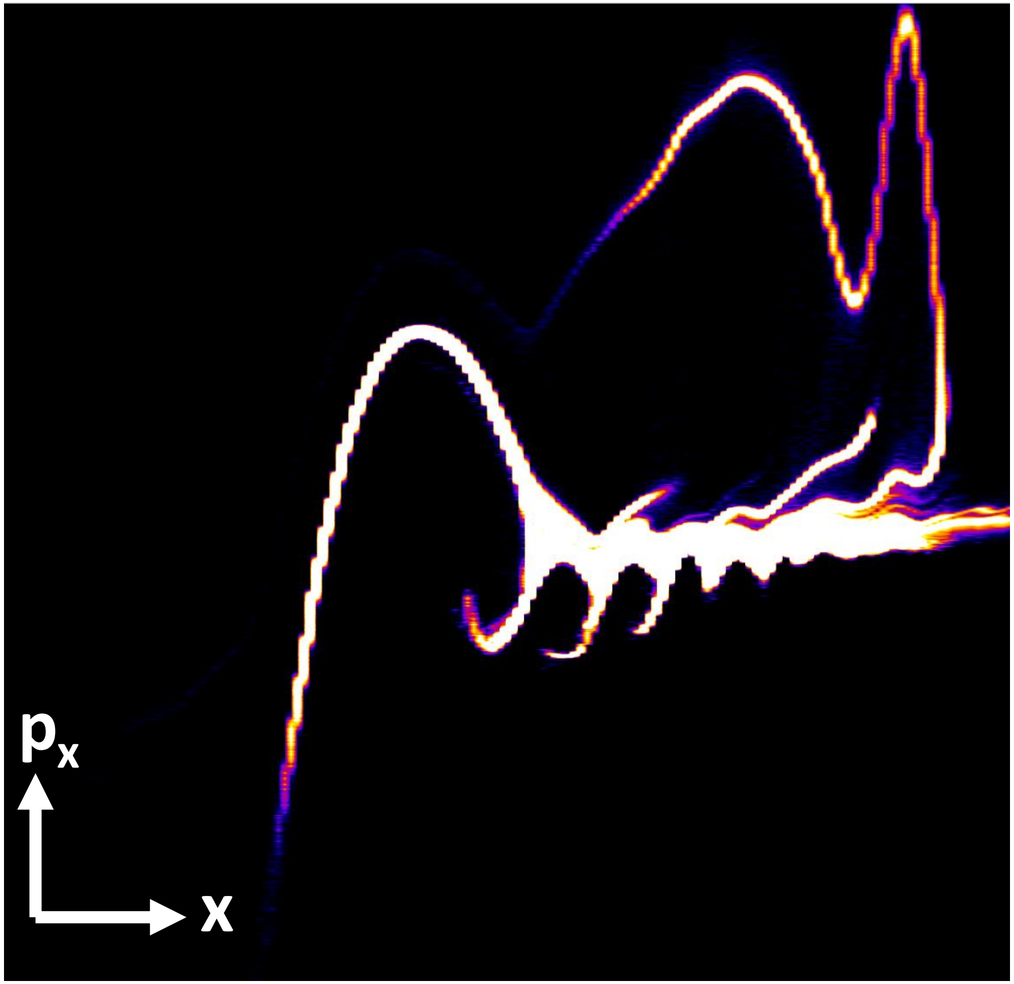


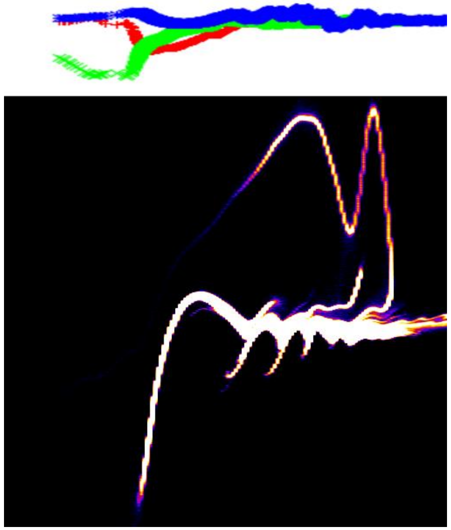
- extraction

Short laser pulse (first period)



blue: Ex
green: Ey
red: Bz

- extraction
- reflection in B field



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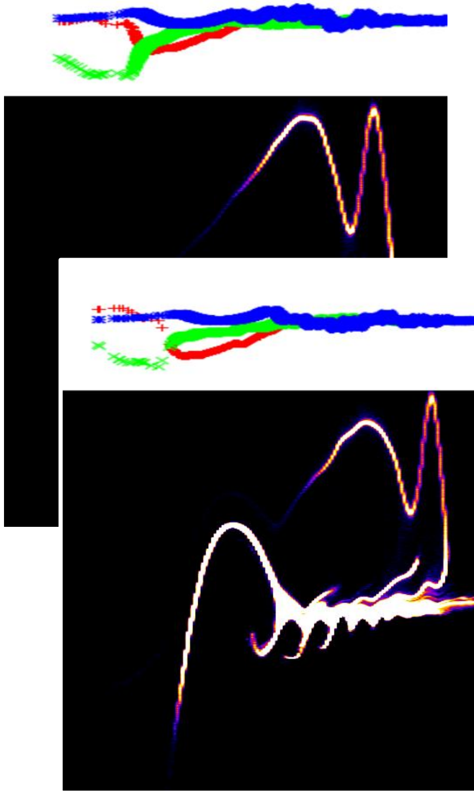
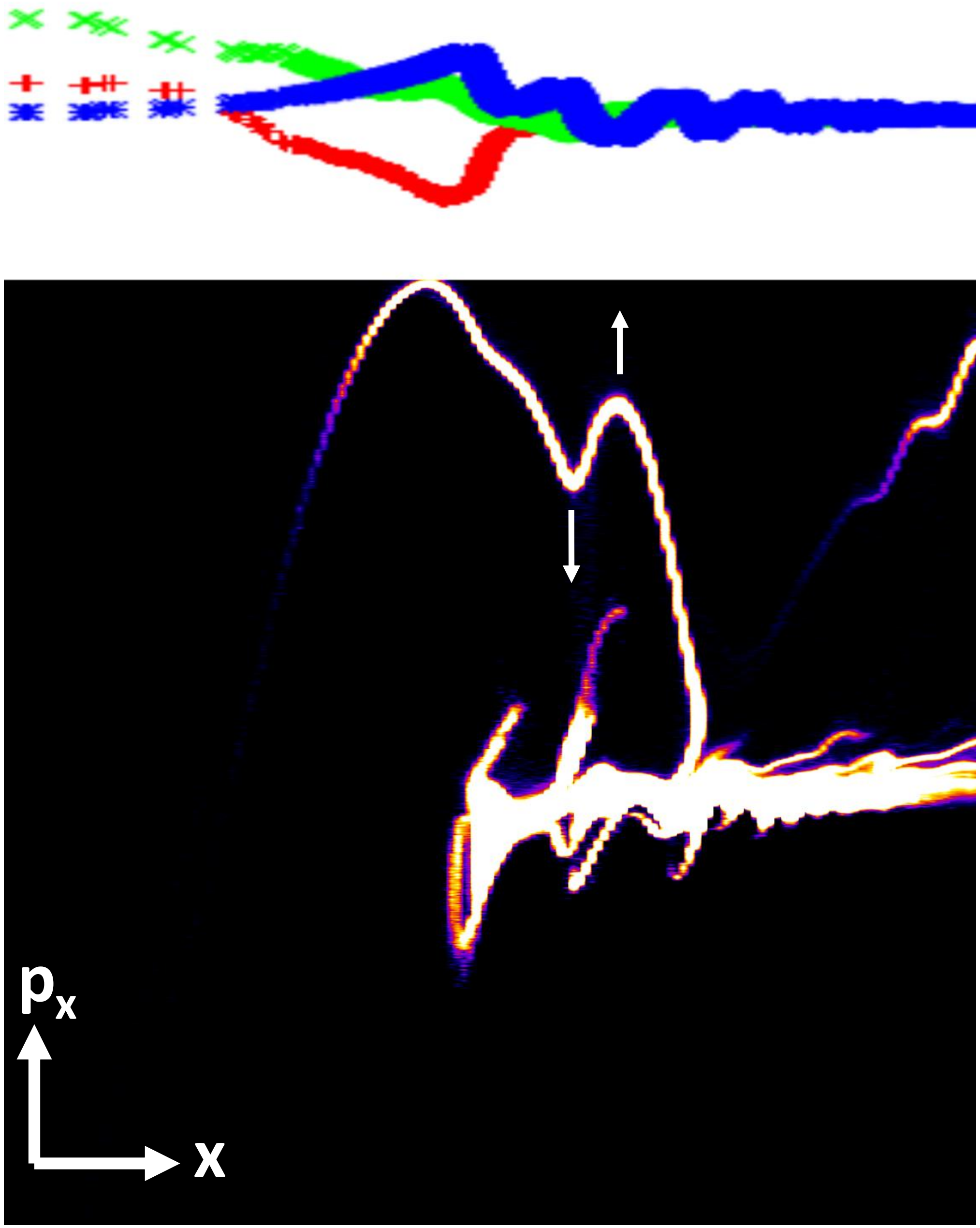
Short laser pulse (first period)

blue: Ex
green: Ey
red: Bz

- extraction
- reflection in B field
- modulation in transient ambipolar field

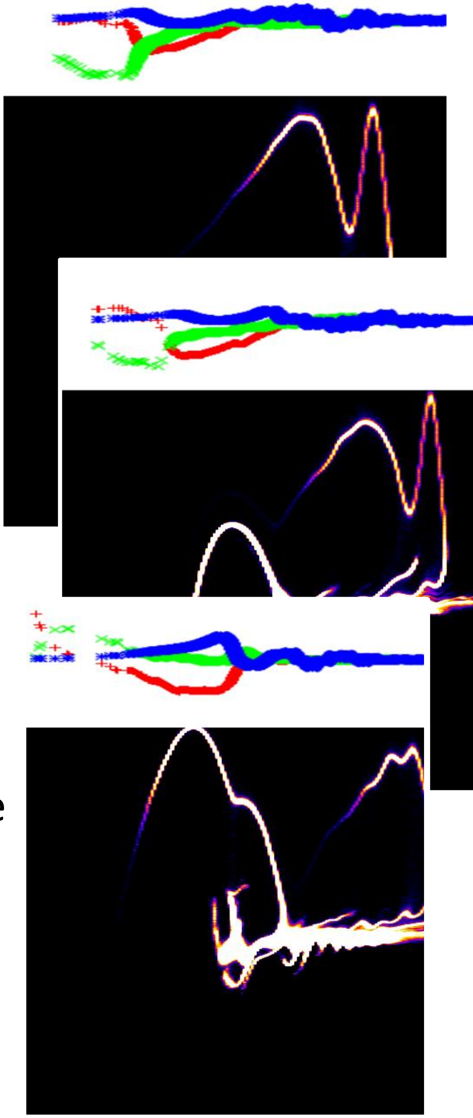


Short laser pulse (first period)

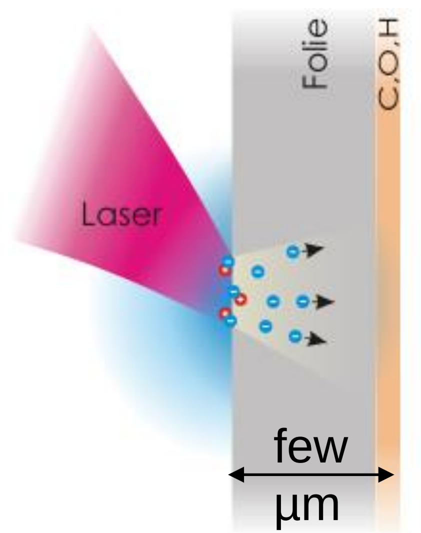


blue: Ex
green: Ey
red: Bz

- extraction
- reflection in B field
- modulation in transient ambipolar field
- plasma wave interaction



Energy flux conservation including spectro-temporal distribution



$f_t(t)$?

$p_z(t)$?

$\gamma_h(t)$?

?

Let $n_{e,hot}(t) \equiv n^0_{e,hot} f_t(t)$, then

$$\frac{\chi a_0^2}{2} = n^0_{e,hot} \langle f_t(t)(\gamma_h(t) - 1) m_e v_z(t) \rangle_t$$

and

$$j_h(t) = n^0_{e,hot} f_t(t) v_z(t)$$

a

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$v_z(t)\,\rangle$

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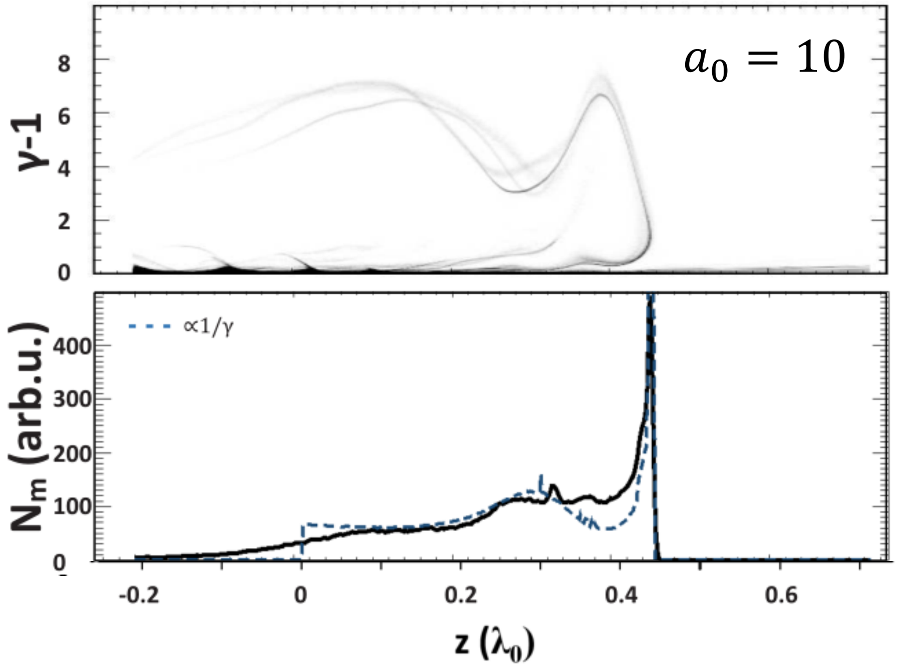
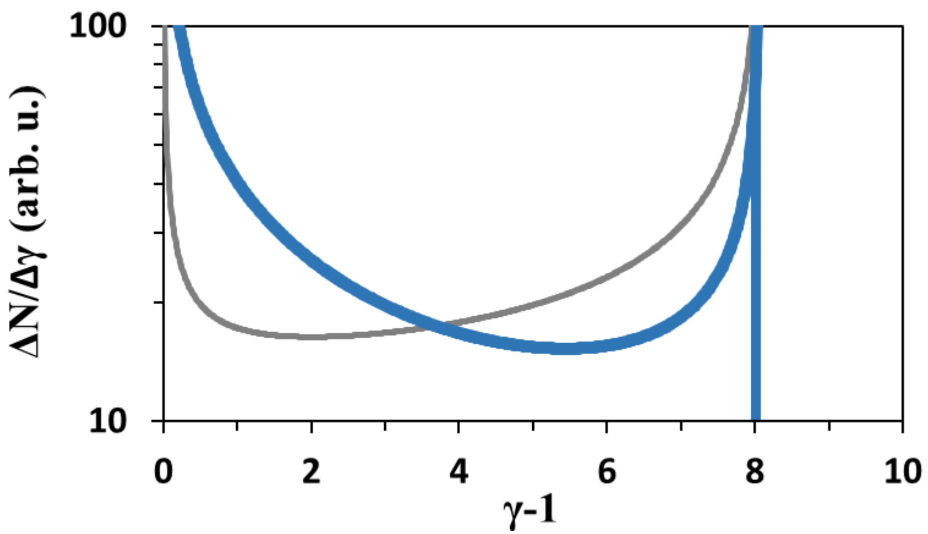
Energy flux conservation including spectro-temporal distribution



- ✓ assuming $f_t(t) \propto \gamma_h(t)^{-1}$ [1]
- ✓ and $p_z(t) = \sqrt{\gamma_h(t)^2 - 1}$
- (✓)and $\gamma_h(t) \cong \sqrt{1 + \hat{a}_0^2 \sin^2 t}$

[1] PRL **107** 205003 (2011)

Energy flux conservation including spectro-temporal distribution



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- ✔ and $p_z(t) = \sqrt{\gamma_h(t)^2 - 1}$
- (✔) and $\gamma_h(t) \cong \sqrt{1 + \hat{a}_0^2 \sin^2 t}$

- **not** Maxwellian or exponential
- peak at high energies
- Shape depends on $\mathbf{f_t}$

Simple comparison - spectrum:

$$f_\gamma(\gamma_h) = \frac{\mathrm{d}N}{\mathrm{d}t}\frac{\mathrm{d}t}{\mathrm{d}\gamma_h} = \frac{f_t}{\dot{\gamma}_h}$$

$$f_\gamma(\gamma_h) = \frac{\pi}{2K(-a_0^2)} \frac{1}{\sqrt{(\gamma_h^2-1)(a_0^2-\gamma_h^2+1)}}$$

[1] PRL **107** 205003 (2011)

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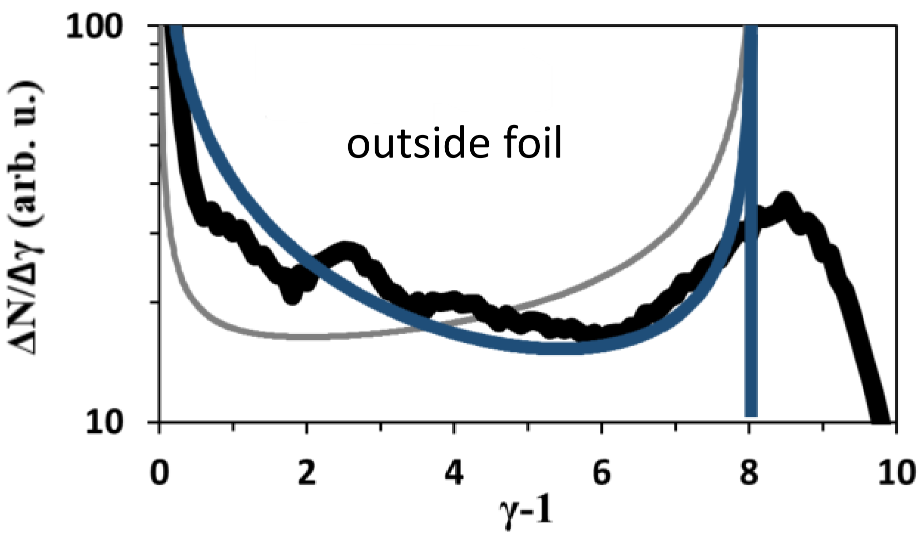
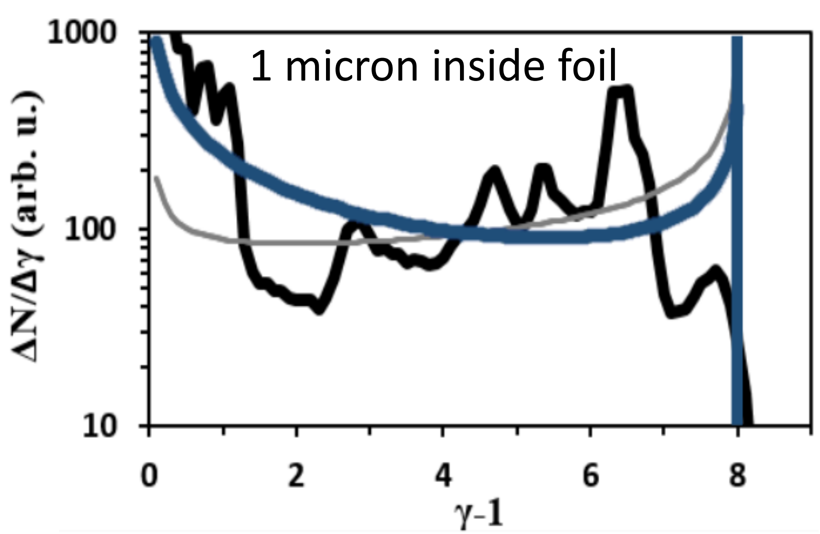
Energy flux conservation including spectro-temporal distribution





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Simple comparison - spectrum:

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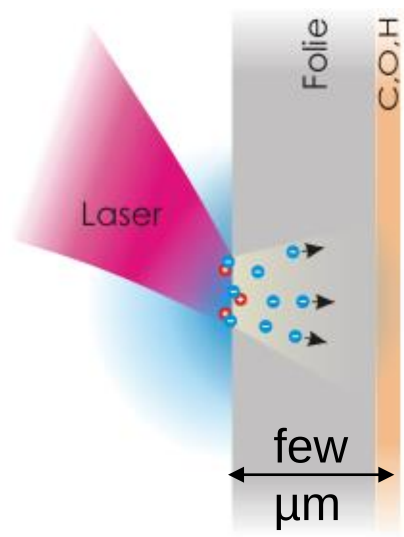
$$f_\gamma(\gamma_h) = \frac{\pi}{2K(-a_0^2)} \frac{1}{\sqrt{(\gamma_h^2-1)(a_0^2-\gamma_h^2+1)}}$$

[1] PRL **107** 205003 (2011)

Temporal variation of current (within a bunch)



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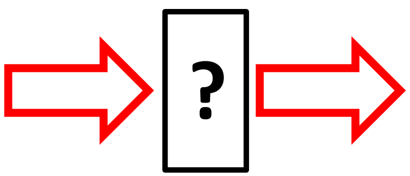
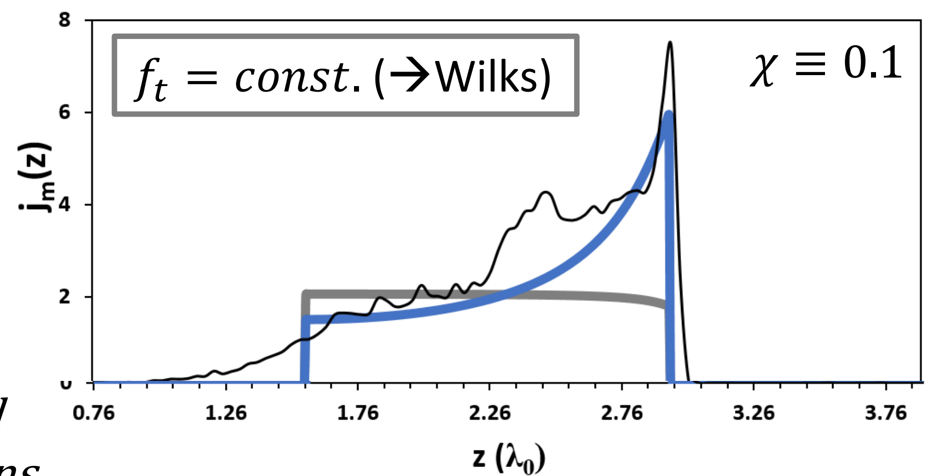




absorbed energy (per unit area and time)

χI

energy carried away by electrons

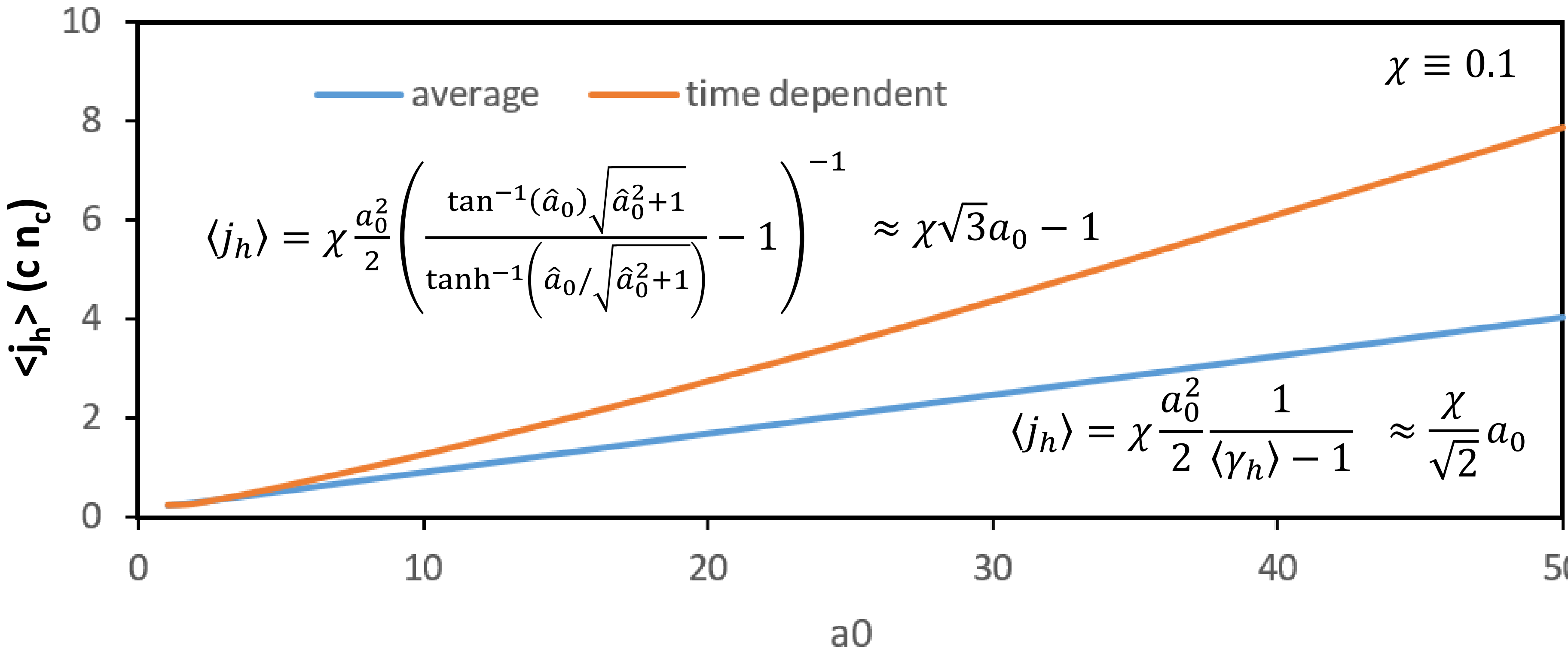
$\langle n_{e,hot}(t)(\gamma_h(t)-1)m_e v_z(t$

$$\chi \frac{a_0^2}{2} = n_{e,hot}^0 \langle f_t(t)(\gamma_h(t)-1)v_h(t)\rangle$$

$$j_h(t) = n_{e,hot}^0 f_t(t) v_h(t)$$

$$j_h(t) = \chi \frac{a_0^2}{2} \frac{1}{\left\langle \frac{(\gamma-1)\sqrt{\gamma^2-1}}{\gamma^2} \right\rangle} \frac{\sqrt{\gamma(t)-1}}{\gamma(t)^2}$$

Comparison average currents



DRESDEN concept

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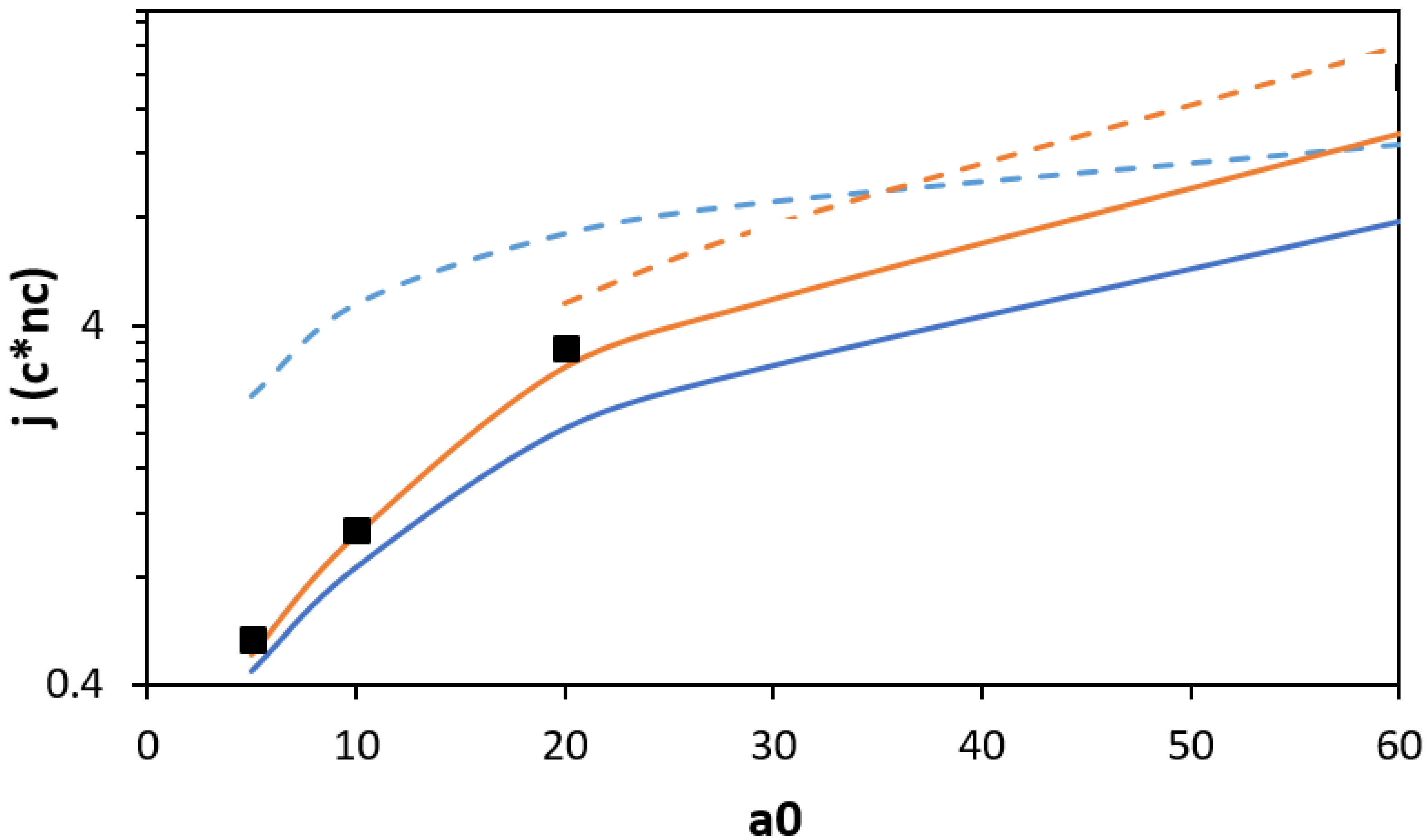
Average current

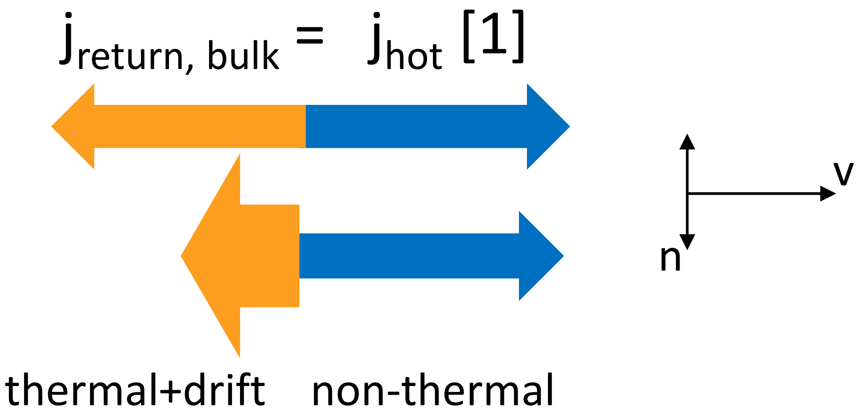


energy flux conservation solved with

$\gamma_h n_c c$

- **time-dependent** variables, assuming quiver motion
- average, **constant** variables, assuming quiver motion
- time-dep. variables assuming $\boldsymbol{\gamma_h(t)}$ **modified** for co-moving e - in surface fields (PRL **107** 205003 (2011))

Impact on Ohmic heating

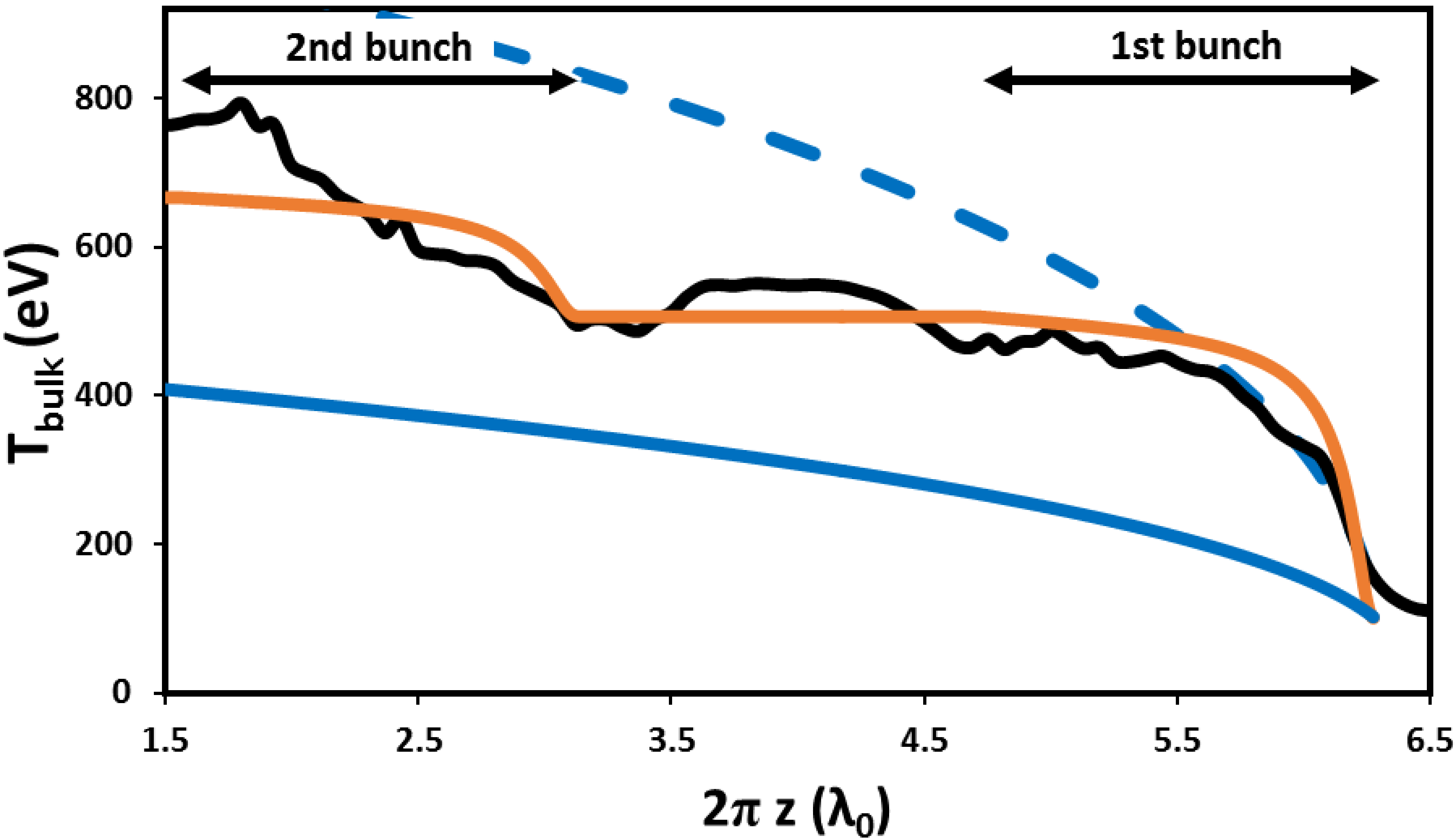


- return current is **slow** ($n_{e,hot}/n_{bulk}$)
- **Ohmic heating** effective [2]:
  $\frac{3}{2} n_{e,bulk} \frac{\partial T_{e,bulk}}{\partial t} = \eta j_{hot}^2$ with $\eta \propto Z\Lambda / T_{e,bulk}^{3/2}$ from **Spitzer model**

[1] Plasma Phys. Control. Fusion 39, 653 (1997)
[2] Phys. Plasmas 2, 2796 (1995)

t.kluge@hzdr.de

Impact on Ohmic heating



$\langle j_h \rangle$ from PIC $\quad$ $\gamma_h n_c c$

energy flux conservation solved with

time-dependent variables, assuming quiver motion

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t.kluge@hzdr.de

Conclusions and outlook

- generally, at laser-solid interactions of ultrashort lasers, the accelerated electrons are ***not thermal***

- this can have ***experimentally relevant*** effects:
  - spectrum
  - current
  - Ohmic heating
  - magnetic field generation and collimation
  - Others?

    → Kα yield

    → Kα line broadening and shift
    (which with temperature models need superposition of several temperatures to explain experiments)

    → For ion acceleration, behind foil quick randomization occurs due to static fields.
    Does one see the effect of temporal and spectral structure in ions?

- for **realistic lasers** (prepulses, few cycles, mobile ions + expansion of foil during laser, heating) and thin foils (recirculation) one might still get some ***randomization*** of electron phases = exponential-like spectra

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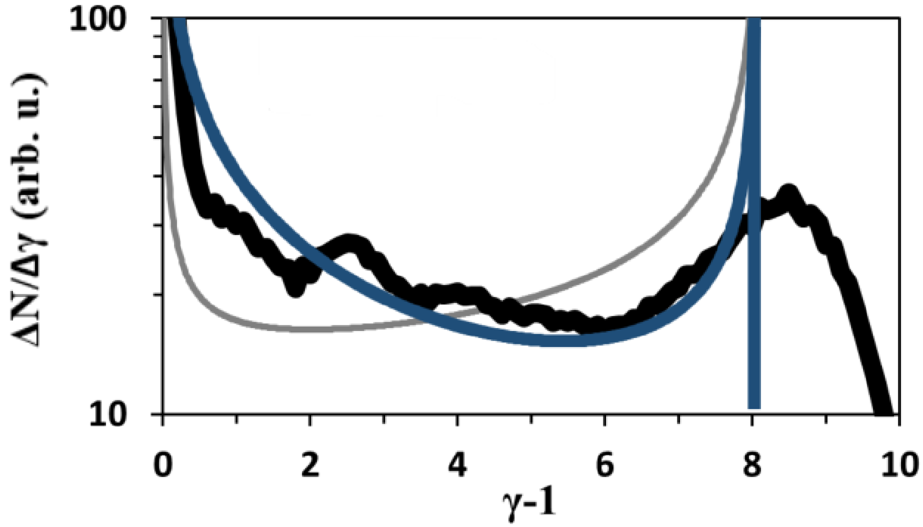
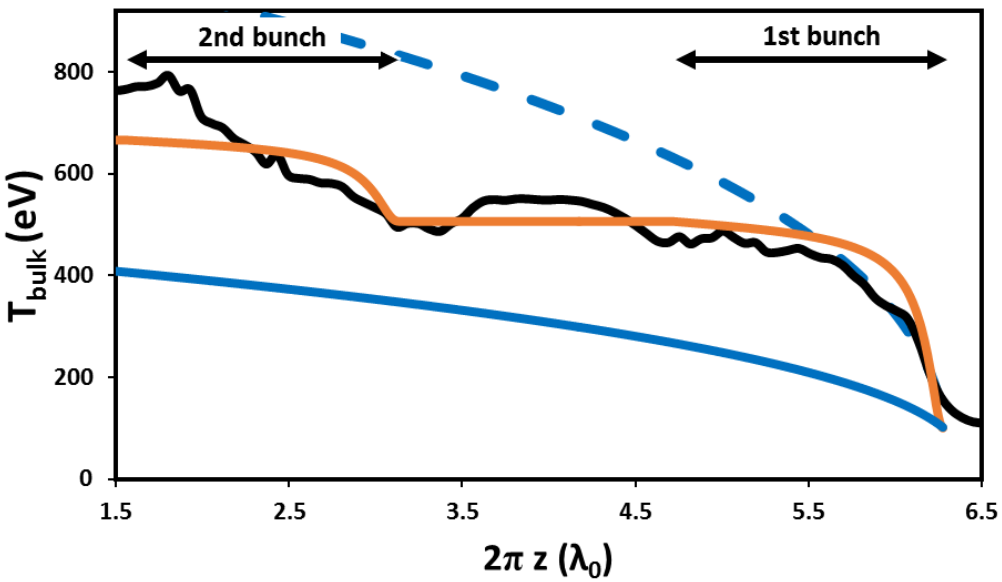
t.kluge@hzdr.de

Conclusions and outlook





constat $\langle j_h \rangle$ from PIC

energy flux conservation solved with **time-dependent** variables

$\gamma_h n_c c$

$$j_h(t) = \chi \frac{a_0^2}{2} \frac{1}{\left\langle \frac{(\gamma - 1)\sqrt{\gamma^2 - 1}}{\gamma^2} \right\rangle} \frac{\sqrt{\gamma(t) - 1}}{\gamma(t)^2}$$

$$\langle j_h \rangle = \chi \frac{a_0^2}{2} \left(\frac{\tan^{-1}(\hat{a}_0)\sqrt{\hat{a}_0^2+1}}{\tanh^{-1}\left(\hat{a}_0/\sqrt{\hat{a}_0^2+1}\right)} - 1 \right)^{-1}$$

$$\approx \boldsymbol{\chi\sqrt{3}a_0 - 1}$$

- ultrashort laser-solid interaction: **non-thermal** energy distribution in energetic bunches
- current $\neq \gamma n_c c$

DRESDEN concept HZDR