Max-Planck-Institut
für Quantenoptik

Relativistic light-electron interactions

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Outline

Relativistic Regime

One particle in a Laserfield

Many particles in Laserfield => Laser Plasma Interaction

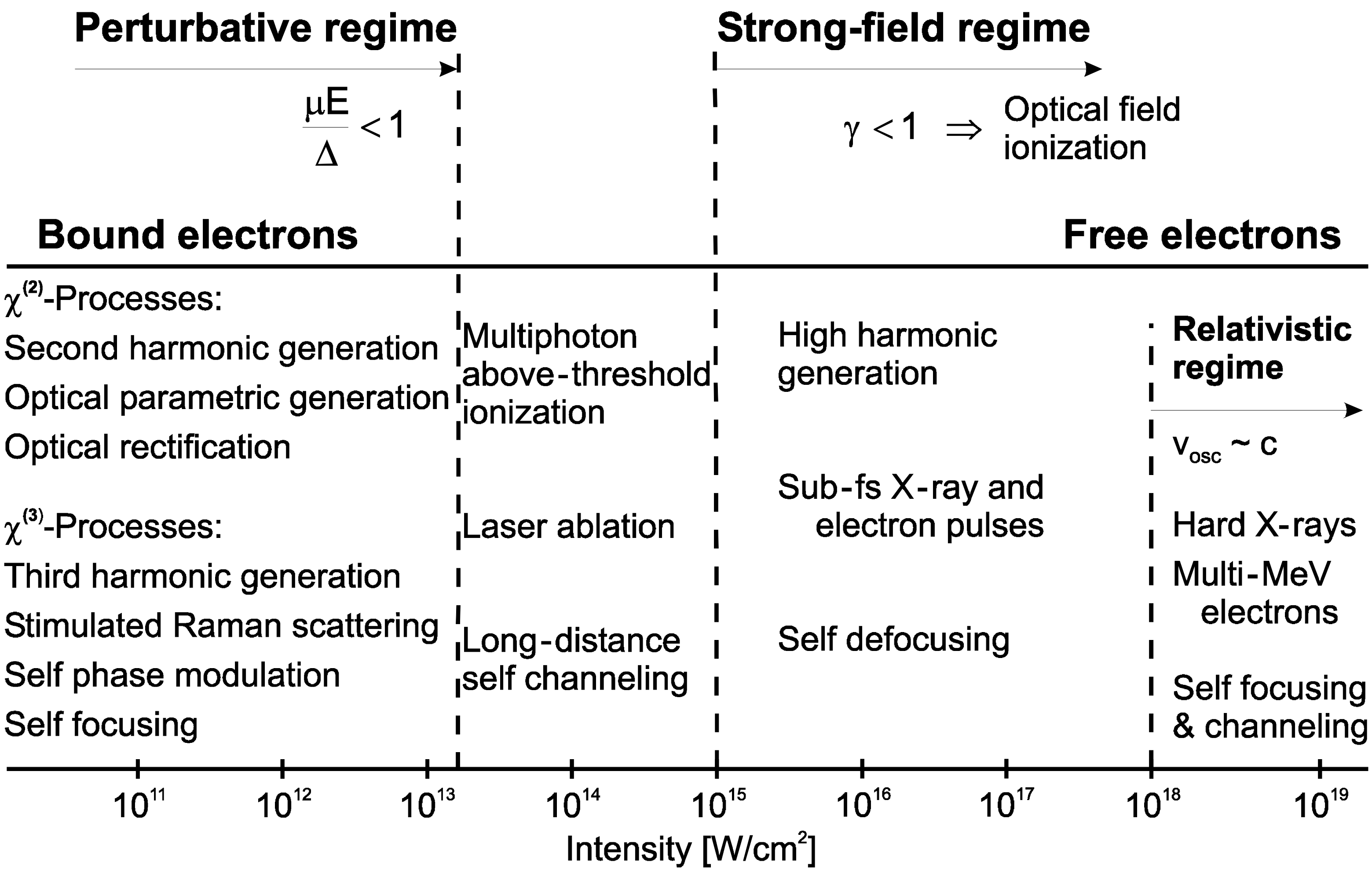
Particle acceleration:

- **Wakefield Acceleration**
- **Bubble acceleration Regime**

MPQ

Relativistic Regime

Regimes of Nonlinear Optics



Particle in a Laserfield

Some definitions: $\vec{E} = -\partial_t \vec{A} - \nabla \varphi \qquad a = \frac{eA}{m_0 c} = -\frac{eE}{m_0 c \omega}$

Intensity of a Laser field:

Intensity can be defined in confusingly (and surprisingly) different ways.

It is defined as (in general!): $\vec{I} = \vec{S} = \vec{E} \times \vec{H}$

In an em-wave: $\vec{H} = \frac{\vec{E}}{Z_0} \Rightarrow I = \frac{E^2}{Z_0}$ Z_0 is the vacuum Resistivity

Clear so far, here I is instantaneous Intensity, but often is I defined as the time average over one laser period:

$$\bar{I} = \langle I(t) \rangle = \frac{1}{Z_0 T} \int_0^T E^2 dt = \frac{E_0^2}{Z_0 T} \int_0^T \cos^2(\omega t) dt = \frac{1}{2} \frac{E_0^2}{Z_0}$$ for linear polarized light

$$= \frac{E_0^2}{Z_0 T} \int_0^T \cos^2(\omega t) + \sin^2(\omega t) dt = \frac{E_0^2}{Z_0}$$ for circular polarized light

Particle in a Laserfield

When we talk here about intensity we mean the **time averaged intensity**

and the laser is always polarized in x-direction and propagates in z-direction:

so: $\vec{a} = a_0 e^{i(\omega t - kz)} \vec{e}_x$

$$I = \frac{1}{2}\frac{E_0^2}{Z_0} = \left(\frac{m_0 c}{e}\right)^2 \frac{1}{2Z_0} \cdot \omega^2 a_0^2 = 2.2 \cdot 10^{22}\, W/m^2 \cdot a_0^2$$

for the common laser wavelength of 800nm

But it is also common to give the intensity in W/cm² so:

$$\boxed{I = 2.2 \cdot 10^{18}\, W/cm^2 \cdot a_0^2}$$

Particle in a Laserfield

Electron in a Laser Field:

here we look at the trajectory of a single electron in a laser field and we neglect the back reactions of the electron motion to the laser propagation

$$\vec{F} = q\vec{E} \qquad m_0 \frac{d\vec{v}}{dt} = q\vec{E} \Rightarrow \vec{v} = \frac{-e}{m_0} \int \vec{E} dt = \frac{e\vec{A}}{m_0} = c\vec{a}$$

a>1 => v>c something is wrong!!

a>1 => relativistic regime => we need to include the magnetic Field

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \qquad \vec{p}(t) = m(t)\vec{v}(t) = m_0 \gamma(t) \vec{v}(t) \qquad \gamma(t) = \frac{1}{\sqrt{1 - \frac{v^2(t)}{c^2}}}$$

Particle in a Laserfield

A plane wave, polarized in x-direction and propagates in z-direction: $\vec{a} = a_0 e^{i(\omega t - kz)} \vec{e}_x$

$$\frac{dp_x}{dt} = -e\left(E_x - v_z B_y\right)$$

$$\frac{dp_z}{dt} = -e v_x B_y$$

$$B = \mu_0 H = \mu_0 \frac{E}{Z_0} = \mu_0 \frac{E}{\sqrt{\frac{\mu_0}{\varepsilon_0}}} = \frac{E}{\sqrt{\frac{1}{\varepsilon_0 \mu_0}}} = \frac{E}{c}$$

Transforming into a moving frame

$$\xi = z \qquad \partial_z = \partial_\xi - 1/c\,\partial_\tau$$

$$\tau = t - z/c \qquad \partial_t = \partial_\tau$$

we obtain for v_x:

$$\partial_\tau v_x = -\frac{e}{m_0} E + \frac{e v_z}{m_0 c} E$$

$$v_x = -\frac{e}{m_0} \int E\, d\tau + \frac{e}{m_0 c} \int E v_z\, d\tau$$

$$v_x = \frac{eA}{m_0} - \frac{eA}{m_0 c} v_z = ca - v_z a$$

Particle in a Laserfield

and for v_z:

$$\partial_\tau v_z = -\frac{e}{m_0} v_x B_y = -\frac{e}{m_0 c} v_x E$$

$$\partial_\tau v_z = -\frac{e}{m_0 c}\left(\frac{e}{m_0} AE - \frac{e}{m_0 c} v_z AE\right) = -\frac{e^2}{m_0^2 c}\left(-\frac{1}{2}\partial_\tau A^2 + \frac{v_z}{c}\frac{1}{2}\partial_\tau A^2\right)$$

$$v_z = \frac{e^2 A^2}{m_0^2 c}\frac{1}{2} - \frac{e^2 v_z A^2}{m_0^2 c^2}\frac{1}{2} = \frac{ca^2}{2} - \frac{v_z a^2}{2}$$

$$v_z = \frac{ca^2}{2+a^2}$$

So finally v_x becomes: $$v_x = ca - \frac{ca^2}{2+a^2} a = \frac{2ca}{2+a^2}$$

Particle in a Laserfield

Electron in a Laser Field:

$$v_x = \frac{2ca}{2+a^2}$$

$$v_z = \frac{ca^2}{2+a^2}$$

$$\gamma = 1 + \frac{a^2}{2}$$

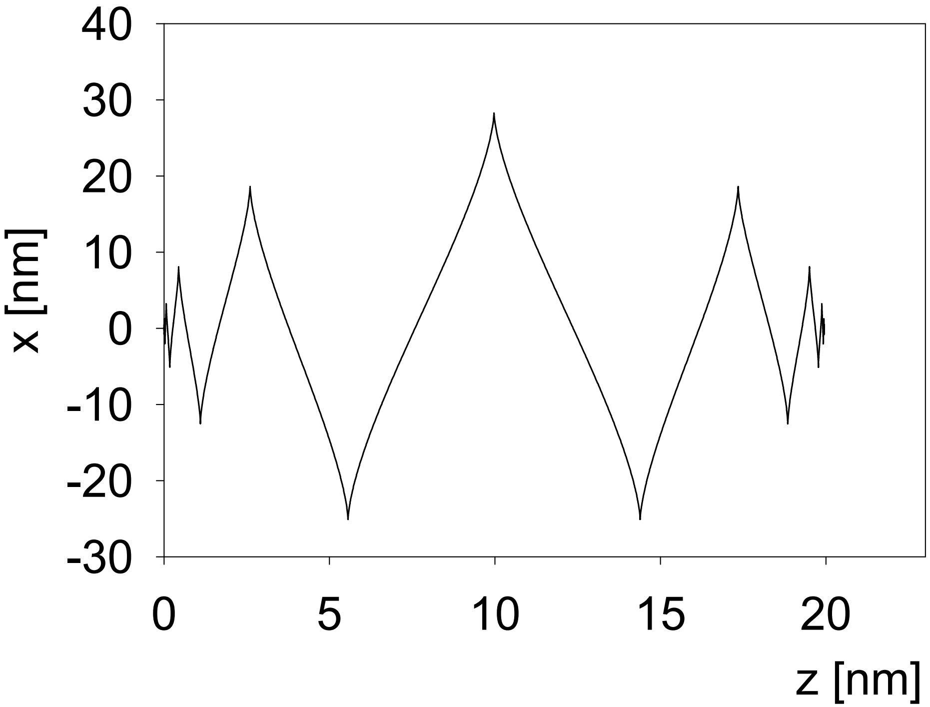
$$E_{kin} = m_0 c^2 (\gamma - 1) = m_0 c^2 \frac{a^2}{2}$$

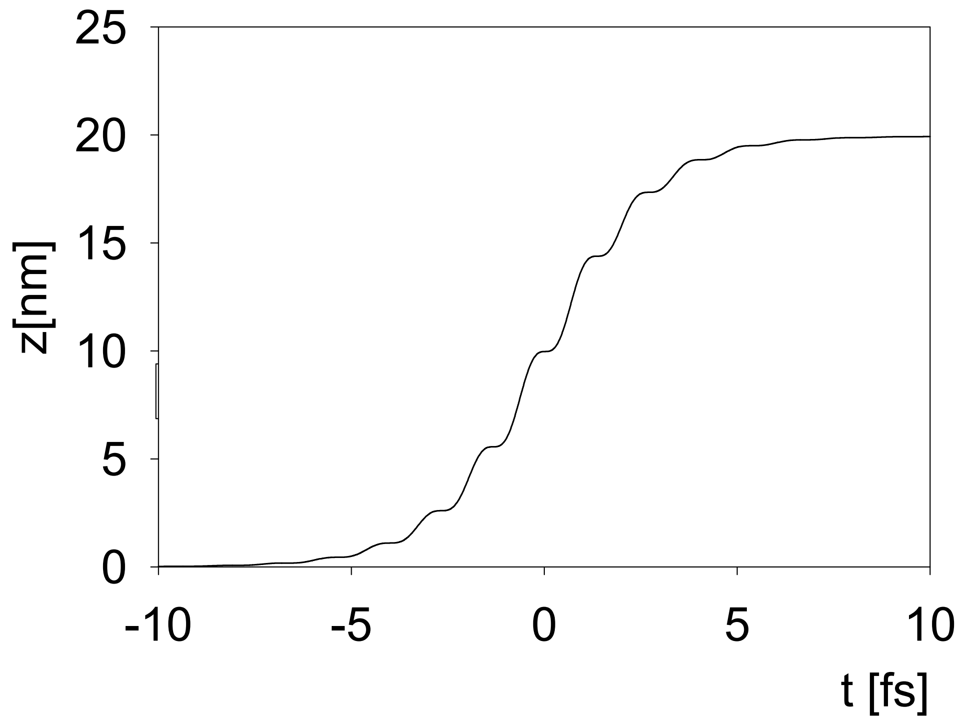
a<<1: $v_x \approx ca$ $\quad v_z \approx \frac{ca^2}{2}$

a>>1: $v_x \approx 0$ $\quad v_z \approx c$

Particle in a Laser field

5 fs, 5*10^{18} W/cm^2





Particle in a Laser field

After the interaction of the electron with the plane Laser wave it has its original velocity

$\Rightarrow$**no energy gain in a plane em-wave!**

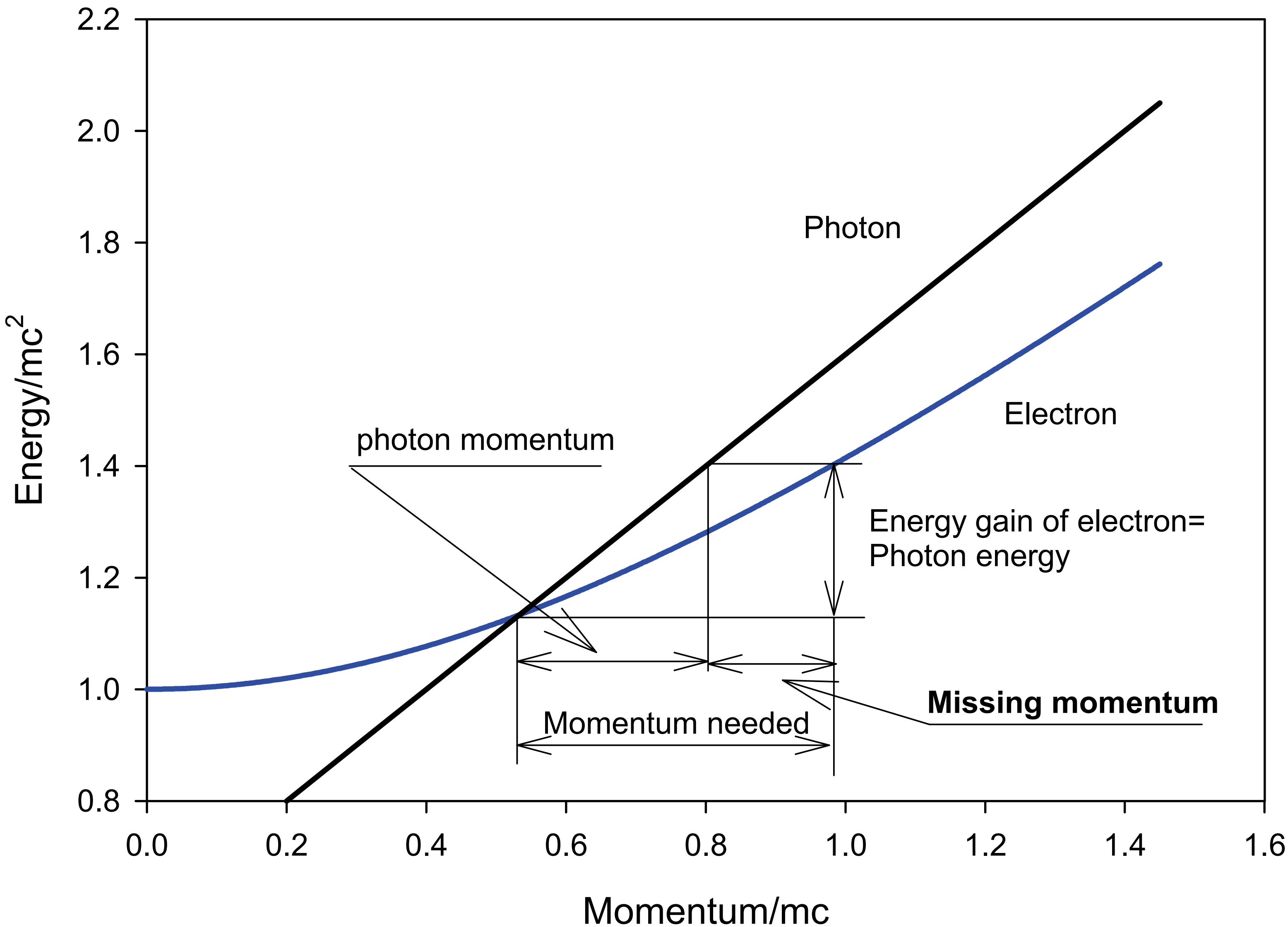
Also from energy and momentum conservation when a photon hits an electron:

after absorption: $\Delta E_{el} = E_{ph} = \hbar\omega, \quad \Delta p_{el} = p_{ph} = \frac{\hbar\omega}{c}$

But: $E_{ph} = cp_{ph} \Rightarrow \frac{dE_{ph}}{dp_{ph}} = c$

$$E_{el} = \sqrt{m_0^2 c^4 + p_{el}^2 c^2} \Rightarrow \frac{dE_{el}}{dp_{el}} = \frac{p_{el} c^2}{\sqrt{m_0^2 c^4 + p_{el}^2 c^2}} < c$$

Particle in a Laser field



Particle in a Laser field

Ponderomotive Potential & Force :

For studying a particle in a Laser field it is convinient to average over the fast oscillating laser field if $\tau_{Laser} >> 2\pi/\omega \approx 2-3\,fs$

$$U_P = \langle E_{kin} \rangle = m_0 c^2 \langle (\gamma - 1) \rangle = m_0 c^2 \left\langle \frac{a^2}{2} \right\rangle = m_0 c^2 \frac{a_0^2}{4}$$

$$\boxed{U_P = \frac{e^2}{m_0} \frac{E_0^2}{4\omega^2}}$$

$$\vec{F}_P = -\vec{\nabla} U_P = -\frac{e^2}{m_0} \frac{1}{4\omega^2} \vec{\nabla} E_0^2$$

Independent of the charge, particles are pushed out of the Laser focus

Laser in an electron gas

What happens, if the electron density becomes higher

Electrons interact with the laser and modify the fields:

$$\vec{\nabla} \times \vec{H} = \vec{J} + \partial_t \vec{D}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \varepsilon_0 \mu_0 \partial_t \vec{E}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{A} = \mu_0 \vec{J} + \frac{1}{c^2}\left(-\partial_t^2 \vec{A} - \vec{\nabla}\partial_t \varphi\right)$$

$$\vec{\nabla}\left(\vec{\nabla} \cdot \vec{A}\right) - \vec{\nabla}^2 \vec{A} = \mu_0 \vec{J} + \frac{1}{c^2}\left(-\partial_t^2 \vec{A} - \vec{\nabla}\partial_t \varphi\right)$$

$$\vec{\nabla}^2 \vec{A} - \frac{1}{c^2}\partial_t^2 \vec{A} = -\mu_0 \vec{J} + \vec{\nabla}\underbrace{\left(\partial_t \frac{\varphi}{c^2} - \vec{\nabla} \cdot \vec{A}\right)}_{=0}$$

The coupling between electrons and fields is J:
Here J comes from free electrons

$$\vec{J} = \rho \vec{v} = -env_x = -enc\frac{2a}{2 + a^2}$$

Laser in an electron gas

$$\partial_z^2 a - \frac{1}{c^2}\partial_t^2 a = \mu_0 enc \frac{2a}{2+a^2}\frac{e}{m_0 c}$$

$$\partial_z^2 a - \frac{1}{c^2}\partial_t^2 a = \frac{\omega_p^2}{c^2}\frac{a}{1+\frac{a^2}{2}}$$

Were we introduced the so called plasmafrequency: $\omega_P = \sqrt{\frac{e^2 n(a(t))}{\varepsilon_0 m}}$

Assume first a<<1 => $\omega_P = \sqrt{\frac{e^2 n}{\varepsilon_0 m}} = const.$ $\frac{a}{1+\frac{a^2}{2}} \approx a$

Ansatz: $\vec{a} = a_0 e^{i(\omega t - kz)}\vec{e}_x$ => $\partial_z^2 a = -k^2 a,\ \partial_t^2 a = -\omega^2 a$

Laser in an electron gas

$$-k^2 a + \frac{\omega^2}{c^2} a = \frac{\omega_p^2}{c^2} a$$

From this we get the dispersions relation for a em-wave propagation in an electron gas:

$$\boxed{\omega_p^2 = \omega^2 - k^2 c^2}$$

$$k = \frac{\omega}{c}\sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

$\Rightarrow$for $\omega > \omega_p$ „underdense"

$\Rightarrow$for $\omega < \omega_p$ „overdense"; no wave propagation

Phasevelocity: $v_{ph} = \frac{\omega}{k} = \frac{c}{\sqrt{1 - \frac{\omega_p^2}{\omega^2}}} > c!!$

Don't panic! Energy and „Information" propagate with the Groupvelocity!!

Groupvelocity: $v_g = \frac{d\omega}{dk} = c\sqrt{1 - \frac{\omega_p^2}{\omega^2}} < c$

Laser in an electron gas

What happens if *a* becomes larger?

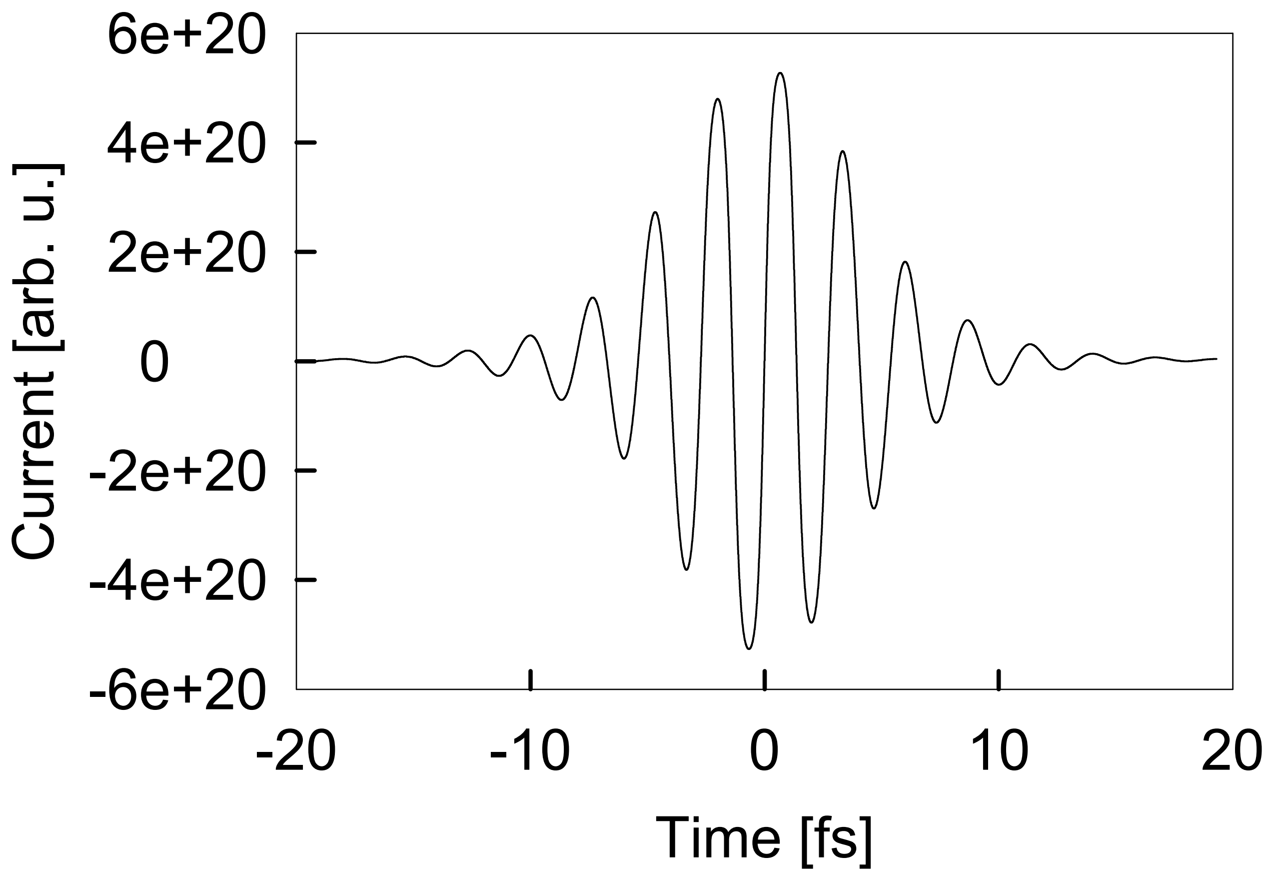
$$\partial_z^2 a - \frac{1}{c^2}\partial_t^2 a = \frac{\omega_p^2}{c^2}\frac{a}{1+\frac{a^2}{2}} \approx \frac{\omega_p^2}{c^2} a \cdot \left(1 - \frac{a^2}{2}\right)$$

⇒for high laser fields the current is reduced compared to the linear current

Laser in an electron gas

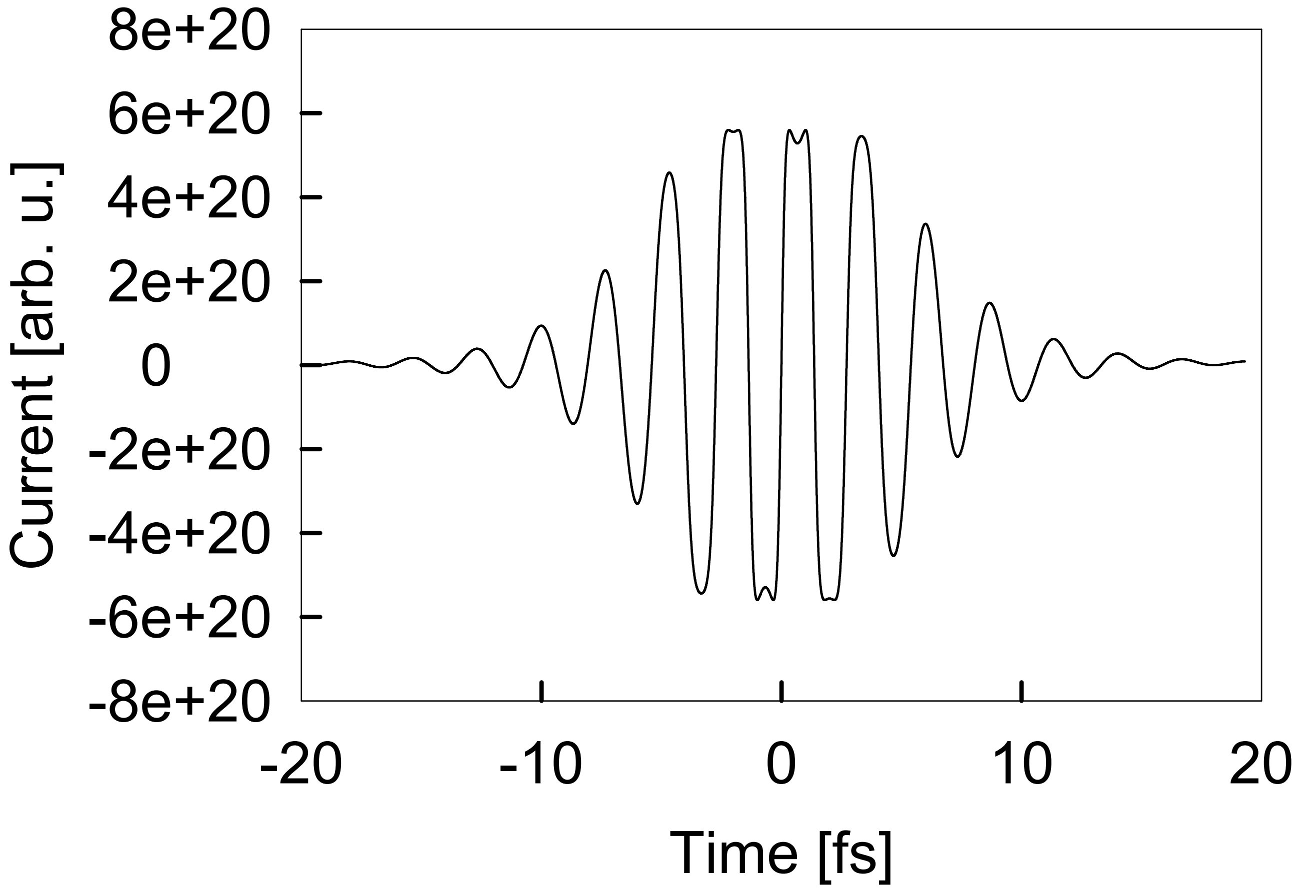
Single electron current

5 fs, a=1; I=2*10^{18} W/cm²



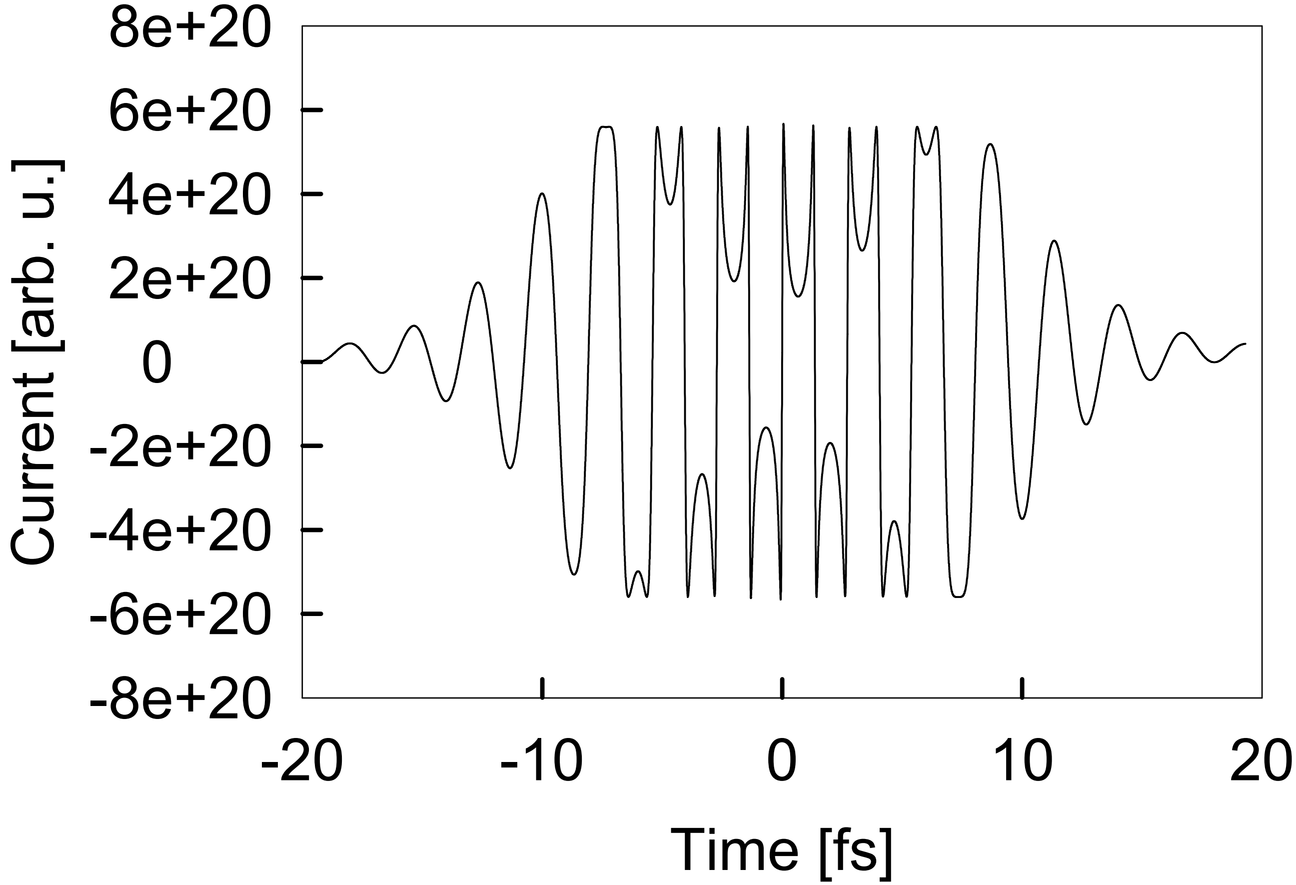
Laser in an electron gas

5 fs, a=2; I=8*10^{18} W/cm²



Laser in an electron gas

5 fs, a=10; I=2*10^{20} W/cm²



Laser in an electron gas

This current should produce huge hamonic radiation, but ist this truthly the case?

NO! Because: $\partial_z^2 a - \frac{1}{c^2}\partial_t^2 a = \frac{\omega(t)_p^2}{c^2}\frac{a}{1+\frac{a^2}{2}}$

Laser pushes electrons towards low E-Fields (Ponderomotive Force) so:

$$\vec{\nabla}\cdot\vec{J} + \partial_t \rho = 0$$

$$1D: \partial_z(nv_z) + \partial_t n = 0$$

$$\xi = z \qquad \partial_z = \partial_\xi - 1/c\,\partial_\tau$$

$$\tau = t - z/c \qquad \partial_t = \partial_\tau$$

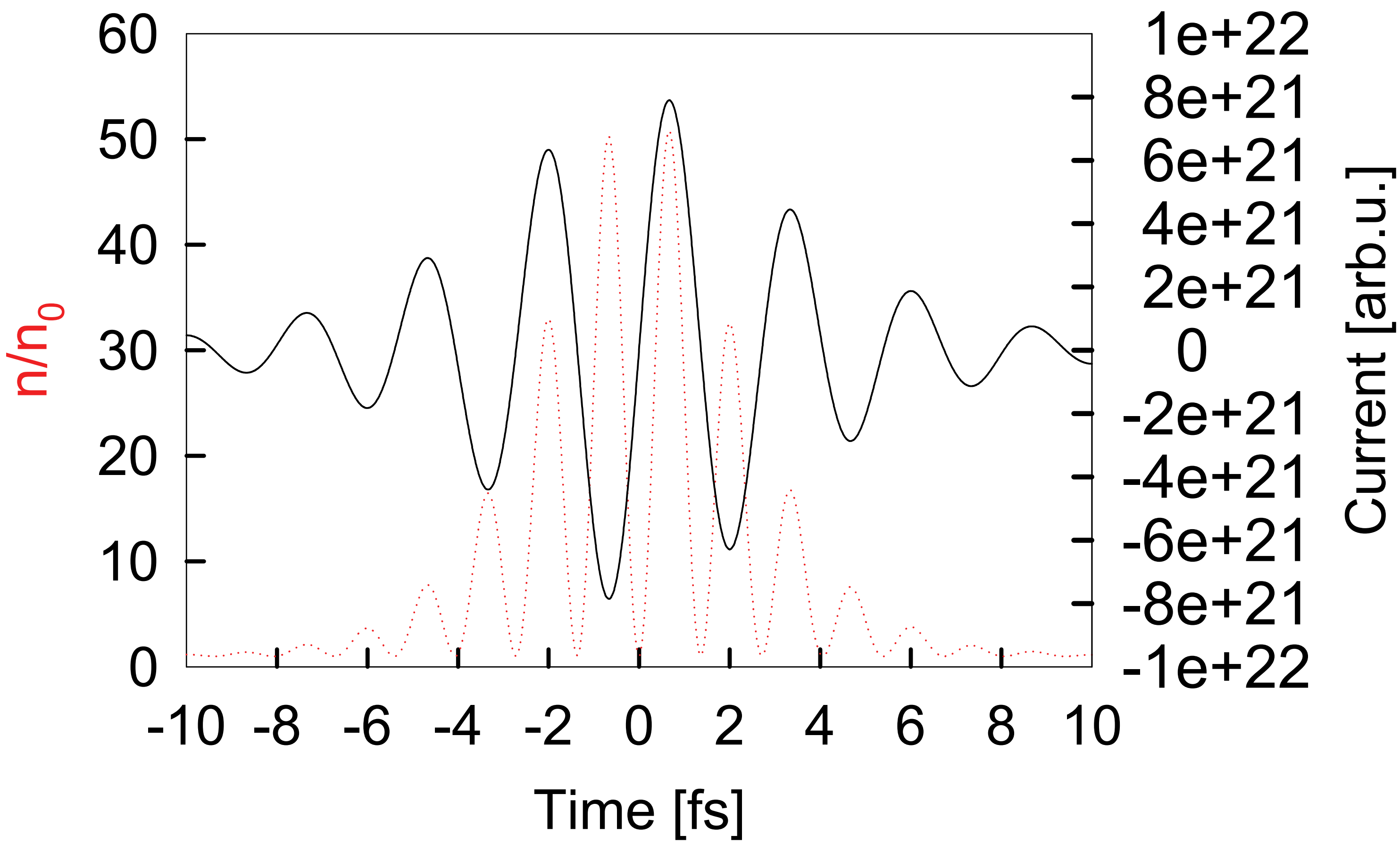
$$\partial_\xi(nv_z) - \partial_\tau(nv_z/c) + \partial_\tau n = 0$$

$$\partial_\tau(-nv_z/c + n) = 0$$

$$n - nv_z/c = n_0 \longrightarrow n(t) = \frac{n_0}{1 - v_z/c} = n_0\left(1 + \frac{a^2}{2}\right)$$

Laser in an electron gas

5fs, a=10; $I=2*10^{20}$ W/cm²



Laser plasma interaction

So far only an electron gas was considered, but normaly a high intensity laser pulse propagates through a plasma with consists of (nearly inmobile) Ions.

How do we have to modify the propagation equation and what happens to the plasma?

$$\frac{dp_x}{dt} = -e\left(E_x - v_z B_y\right)$$

$$\frac{dp_z}{dt} = -ev_x B_y - eE_z$$

The longitudinal electric field comes from density variations:

$$\partial_z E_z = -\frac{e}{\varepsilon}\left(n - n_0\right)$$

The same calculations as for the single particle:

$$v_z = \frac{e^2 A^2}{m_0^2 c}\frac{1}{2} - \frac{e^2 v_z A^2}{m_0^2 c^2}\frac{1}{2} - \frac{e}{m_0}\int E_z dt = \frac{ca^2}{2} - \frac{v_z a^2}{2} + c\phi$$

$$v_z = \frac{ca^2 - 2c\phi}{2 + a^2}$$

$$\phi = \frac{e}{m_0 c}\varphi = -\frac{e}{m_0 c}\int E dt$$

Laser plasma interaction

$$v_x = \frac{2ca(1-\phi)}{2+a^2} \qquad v_z = \frac{ca^2 - 2c\phi}{2+a^2} \qquad n = \frac{n_0}{1 - v_z/c} \qquad \phi = \omega_P^2 \int dt' \int dt'' \left(n/n_0 - 1\right)$$

When a is small => v_z is small => $n \sim n_0$ => $\varphi \sim 0$
⇒NO difference in the propagation equation!!!

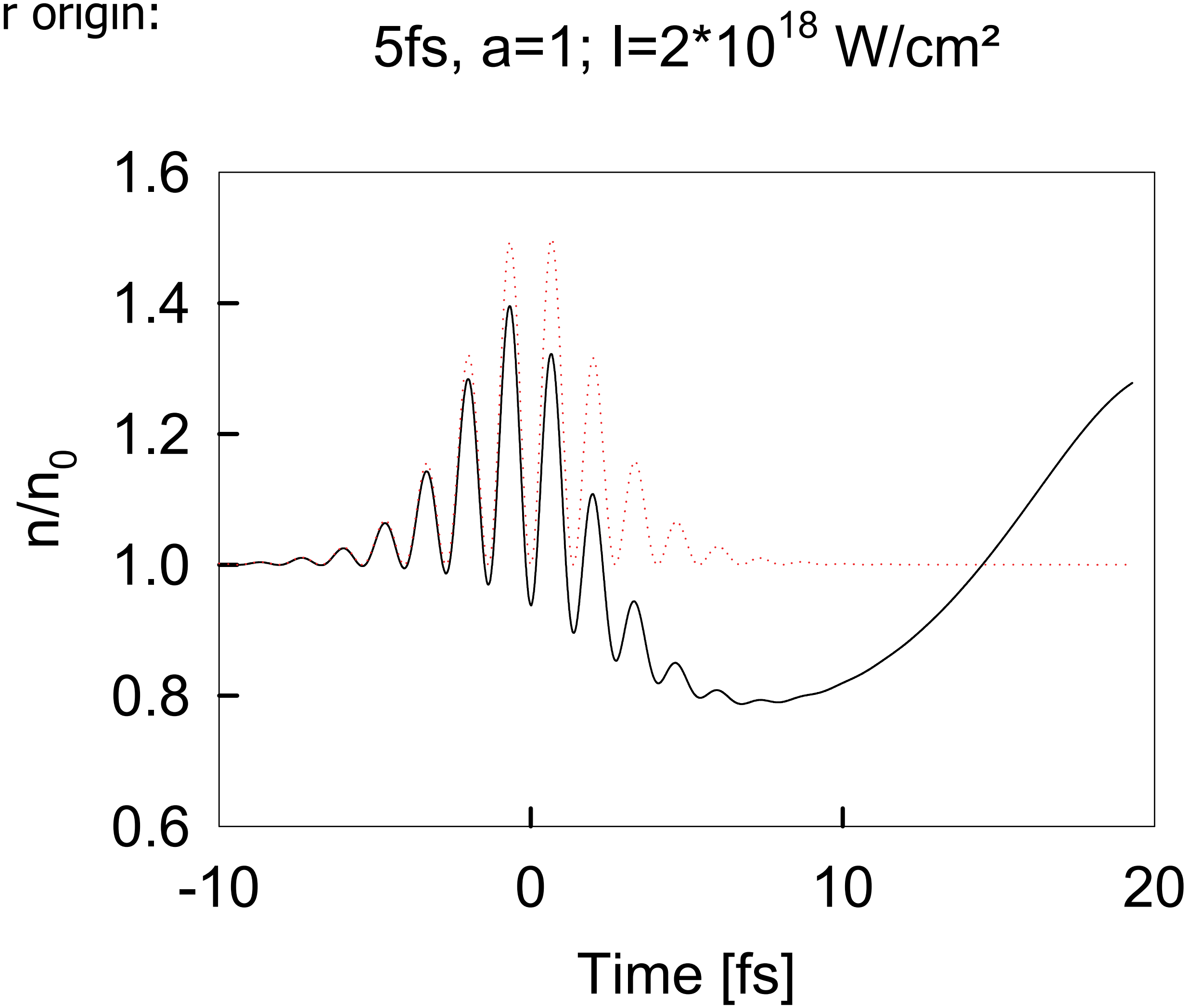
=> a<<1:

$$\partial_z^2 a - \frac{1}{c^2}\partial_t^2 a = \frac{\omega_p^2}{c^2} a \qquad \omega_p^2 = \omega^2 - k^2 c^2$$

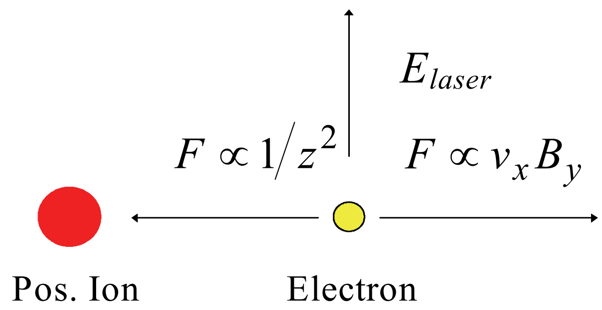
$$v_{ph} = \frac{c}{\sqrt{1 - \frac{\omega_p^2}{\omega^2}}} \qquad v_g = c\sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

Laser plasma interaction

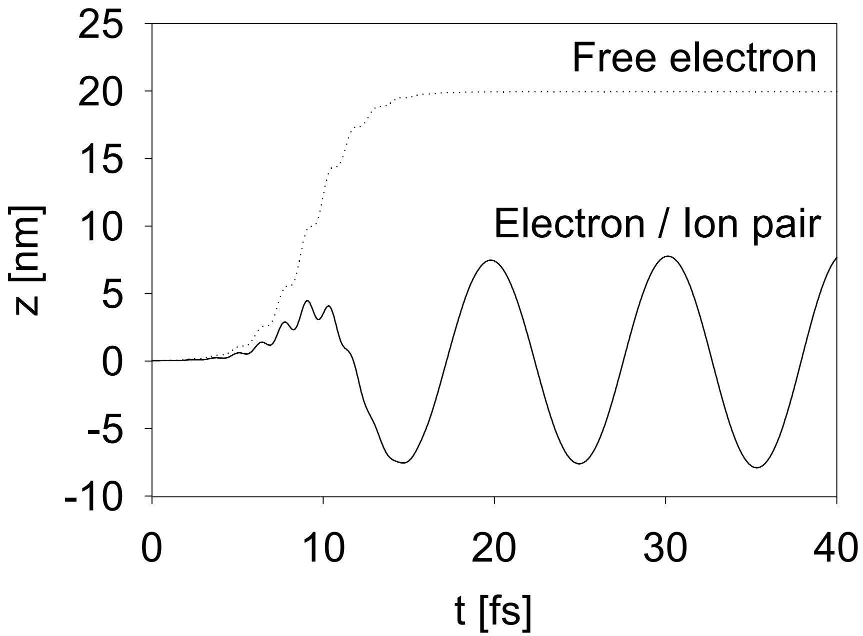
For a>>1 the laser significantly pushes the electrons, which form together with the ions a longithudinal E-Field. After releasing by the laser, the electrons oscillate around their origin:

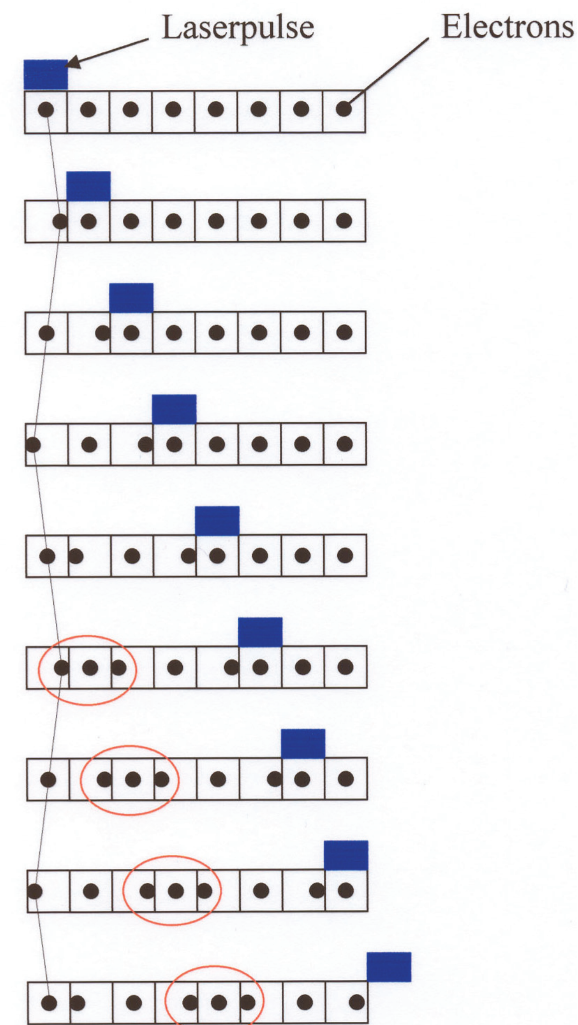


Laser plasma interaction



5 fs, 5*10^18 W/cm^2

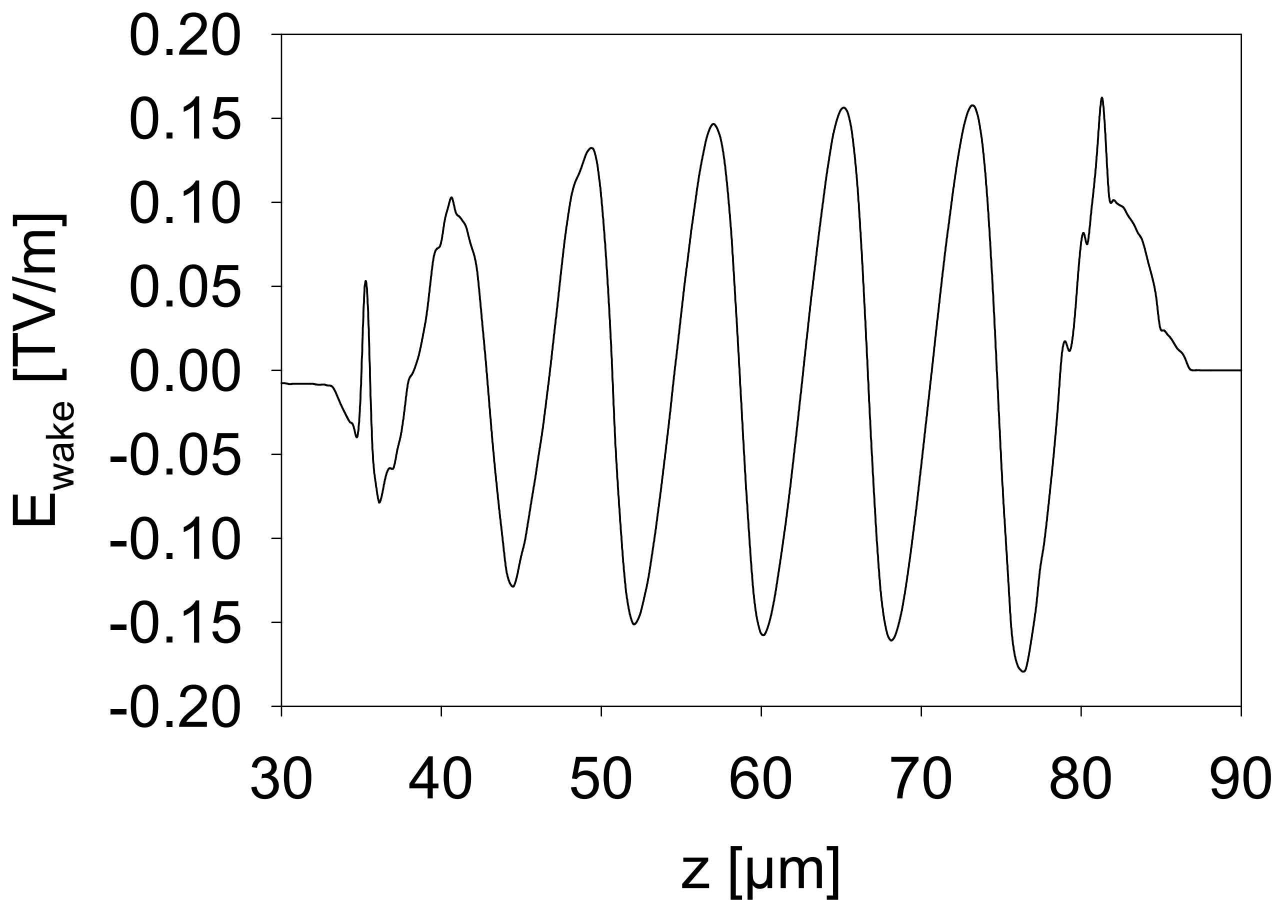




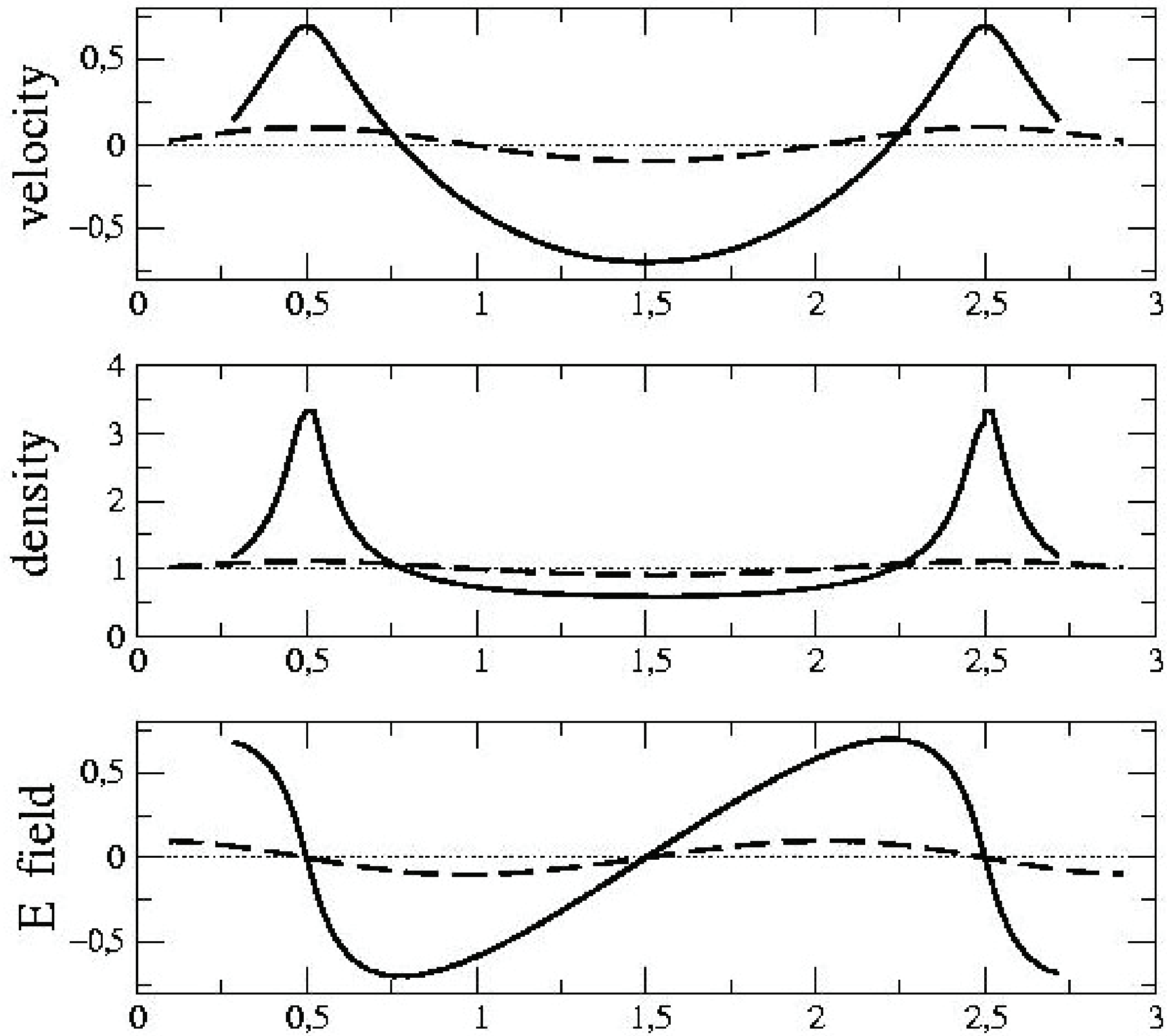
Laser plasma interaction

1D Simulation of Laser-Plasma Interaction:

5fs, $5*10^{18}$ W/cm^2



Laser Wakefield Acceleration



$(x\text{-}v_{ph}t)/\pi$

Tajima, Dawson, PRL43, 267 (1979)

Laser Wakefield Acceleration

Injected electrons can be accelerated by this wakefield:

$$v_{g,l} = c\sqrt{1-\omega_p^2/\omega_0^2}$$

$$\Rightarrow \frac{\omega_0}{\omega_p} = \frac{1}{\sqrt{1-(v_g/c)^2}} = \gamma_p$$

$$v_{ph} = v_{g,l} = c\sqrt{1-\omega_p^2/\omega_0^2},\ v_{el} \approx c$$

$$t_{acc} = \frac{\lambda_p/2}{v_{el}-v_{ph}} = \frac{\lambda_p/2}{c\left(1-\sqrt{1-\omega_p^2/\omega_0^2}\right)} \approx \frac{\lambda_p}{c\left(\omega_p^2/\omega_0^2\right)}$$

$$L_{acc} = ct_{acc} = \frac{\lambda_p}{\left(\omega_p^2/\omega_0^2\right)}$$

Laser Wakefield Acceleration

Dephasing length:

$$L_{acc} = \frac{\lambda_p^3}{\lambda_0^2}$$

Maximum particle energy:

$$W_{\max} \approx \frac{1}{2} L_{acc} e E_{\max}$$

Laser Excitation:

$$E_{\max} / E_0 = \frac{a_0^2}{2\sqrt{1 + a_0^2/2}} \qquad E_0 = \frac{m_0 c \omega_p}{e}$$

Wavebreaking limit:

$$E_{wb} / E_0 = \sqrt{2\left(\frac{\omega_0}{\omega_p} - 1\right)}$$

$$a_{wb} \approx \sqrt{\frac{2\omega_0}{\omega_p} - 1} \quad for\, \omega_0 >> \omega_p$$

Summary of the first part:

1D Laser Plasma model*: $\partial_z^2 a_x - \frac{1}{c^2}\partial_t^2 a_x = \mu_0 e n v_x$ $\quad v_x = \frac{2ca(1-\phi)}{2+a^2}$ $\quad v_z = \frac{ca^2 - 2c\phi}{2+a^2}$

$$n = \frac{n_0}{1 - v_z/c} \qquad \phi = \omega_P^2 \int dt' \int dt''\left(n/n_0 - 1\right)$$

This leads to

Excitation of plasmawaves: $E_{max}/E_0 = \frac{a_0^2}{2\sqrt{1+a_0^2/2}}$

for electron acceleration to $W_{max} \approx \frac{1}{2}\frac{\lambda_p^3}{\lambda_0^2} eE_{max}$

1D Propagation effects: $L_{laser} < \lambda_p$: Selfphase modulation

Wakefield acceleration calls for low densities => high $E_{wb,}$ high energy gain

* see also P.Spangle et. Al PRA **41**, 4463 (1990) and/or Lecture Notes by J. Meyer-ter-Vehn

Summary of the first part:

In theory Laser Wakefield acceleration is fine but:

Laser must be shorter than plasma wavelength to efficiently excite a plasma wave

Plasma wave must not break

Long interaction distance => guiding of the laser

Electrons must be injected in phase with the plasma wave

So WHY Laser Electron Acceleration?

Second Part:

Advantages of Laser wakefield acceleration:

High acceleration fields: TV/m instead of MV/m

Short acceleration distances: mm instead of km

(Train of) short electron bunches

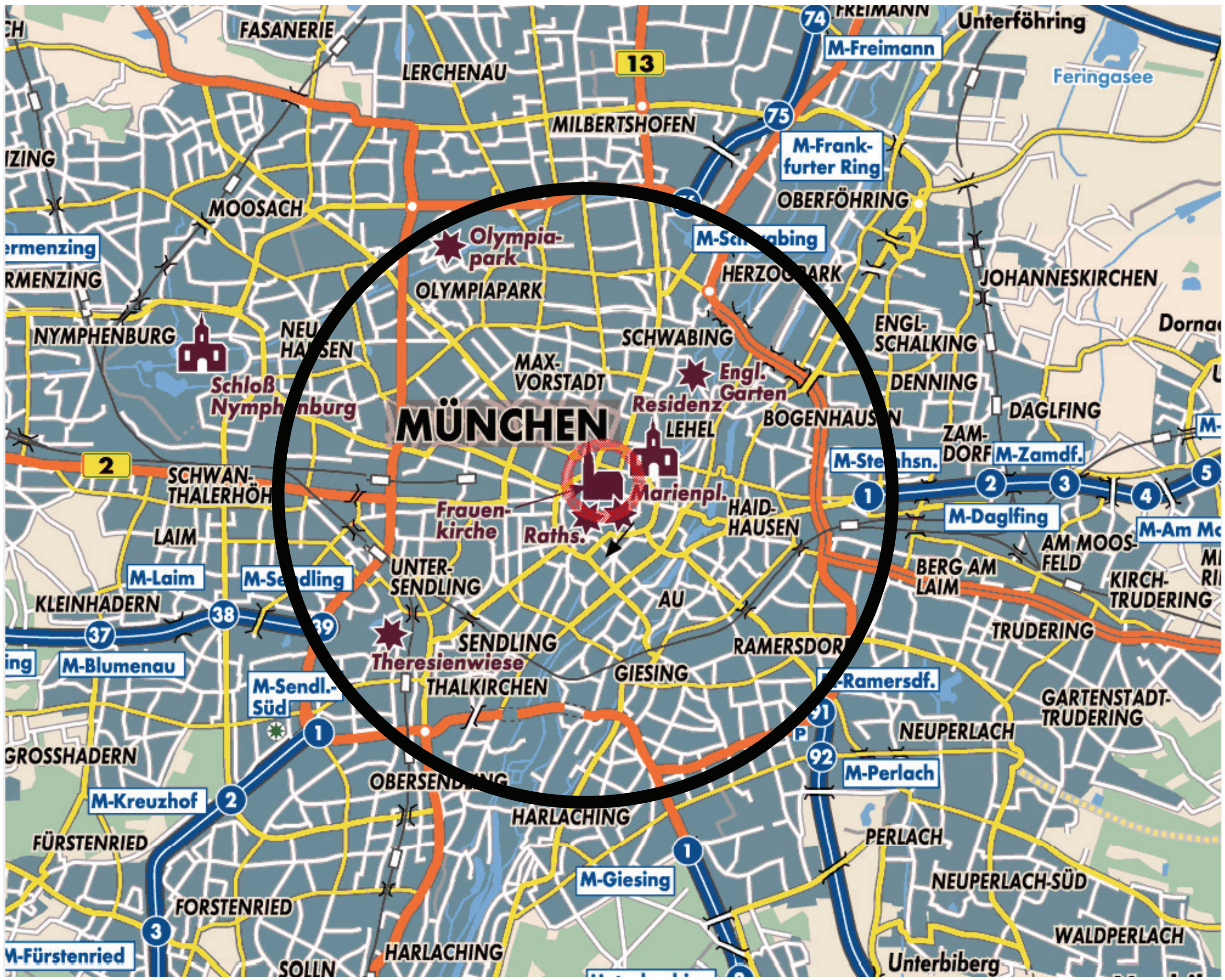
Low emittance

Second Part:

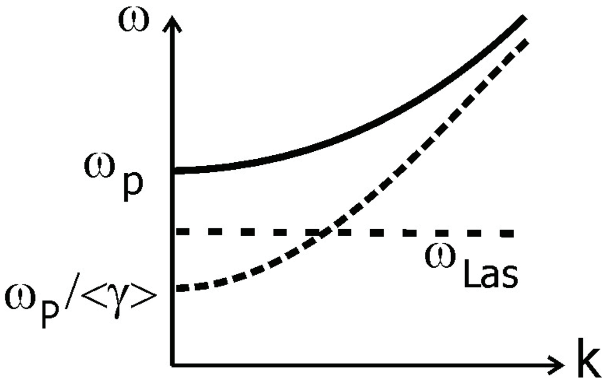
- Relativistic nonlinear optics; what changes in 3D?
- Bubble acceleration regime

Second part

Particle Accelerator are HUGE. Here München vs. CERN:



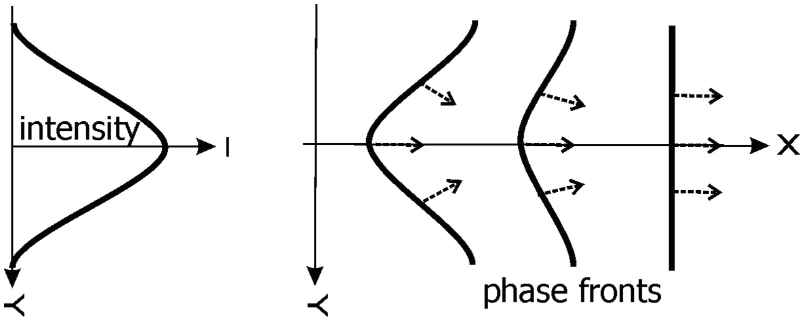
Relativistic nonlinear optics



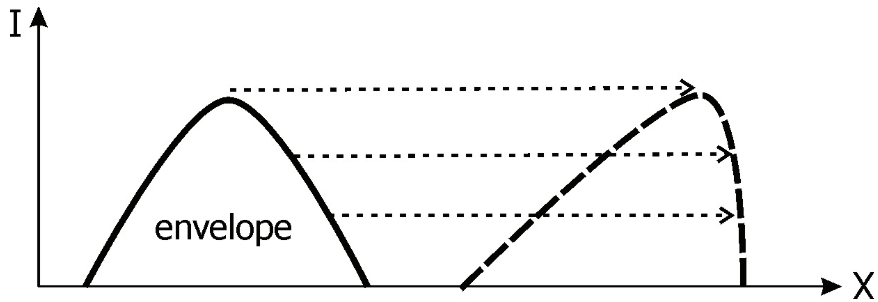
$$n_R = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} = \sqrt{1 - \frac{\omega_{p0}^2}{\omega^2}\frac{1}{\gamma}}$$

When the intensity is high
n_R becomes high

Self-focussing: $v_{ph} = c/n_R$

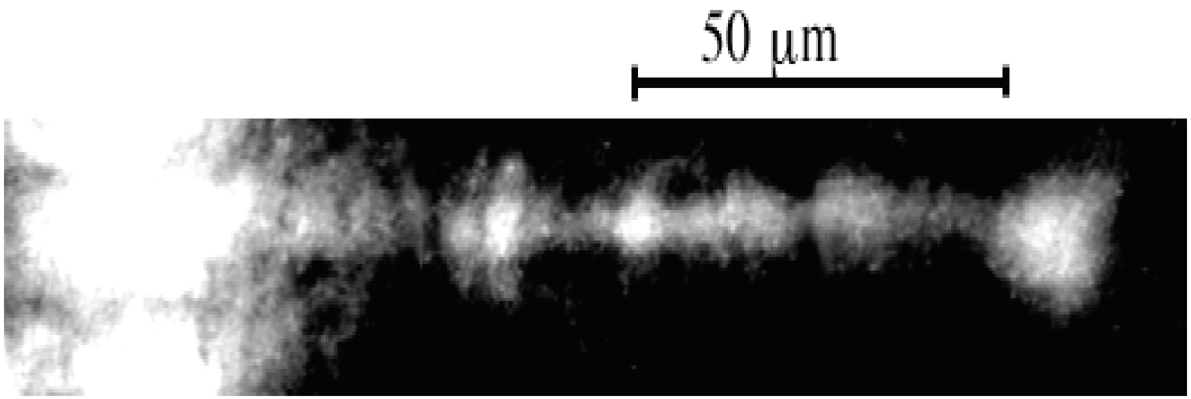


Profile steepening: $v_g = cn_R$

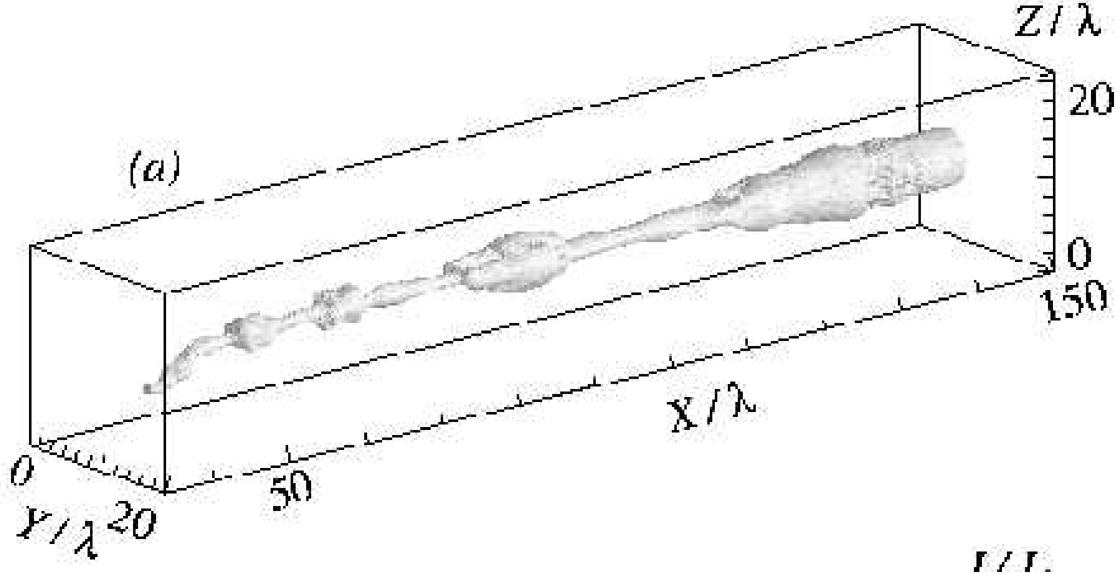


Relativistic nonlinear optics

First observation of relativistic self-focussing



Laser ←

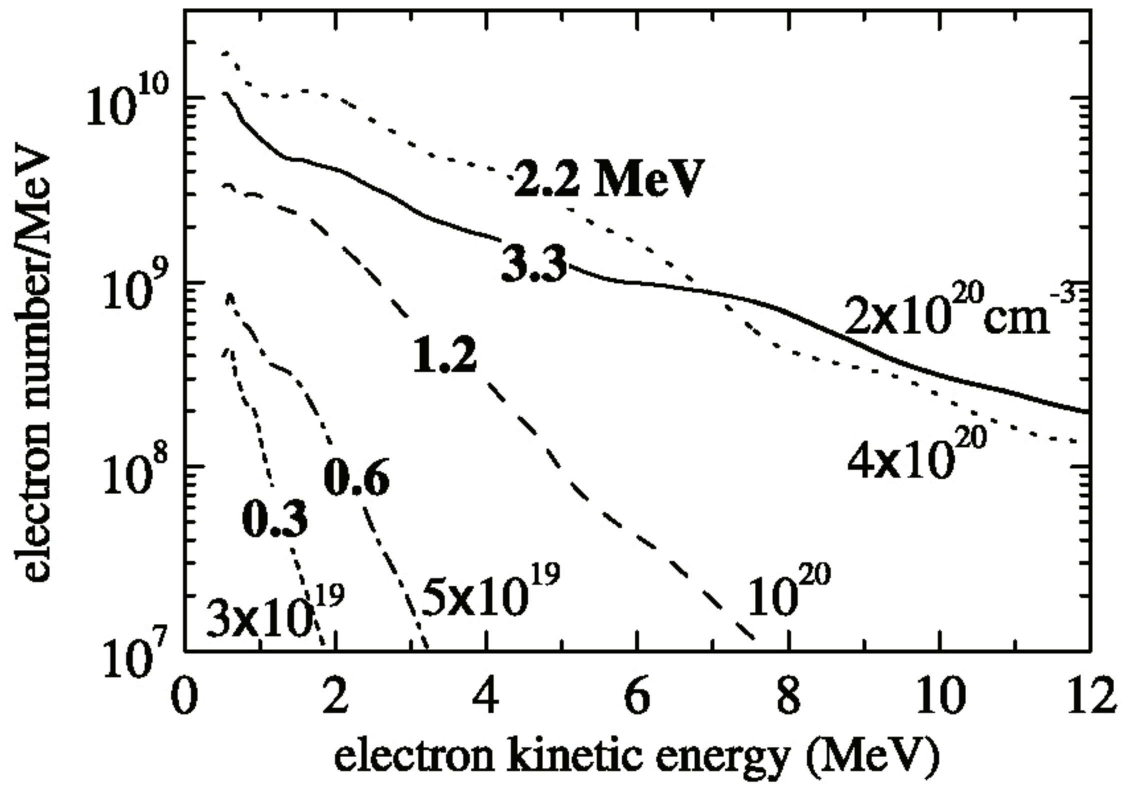


PIC simulation

Borghesi et al., PRL 78, 879 (1997)

Laser Wakefield Acceleration

$4x10^{18}W/cm^2$, 200fs



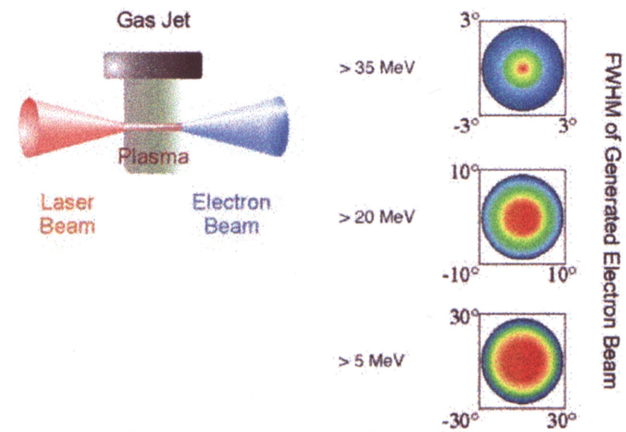
Gahn et al. PRL **83**, 4772 (1999)

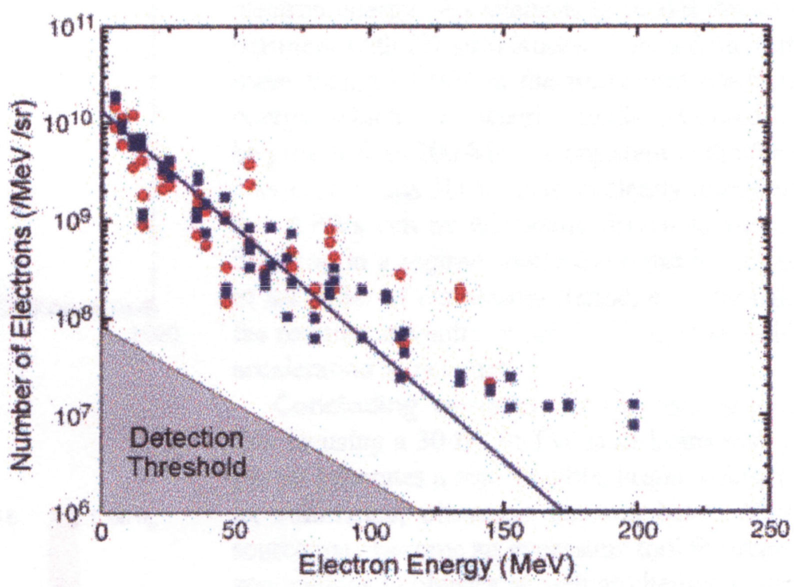
Laser Wakefield Acceleration

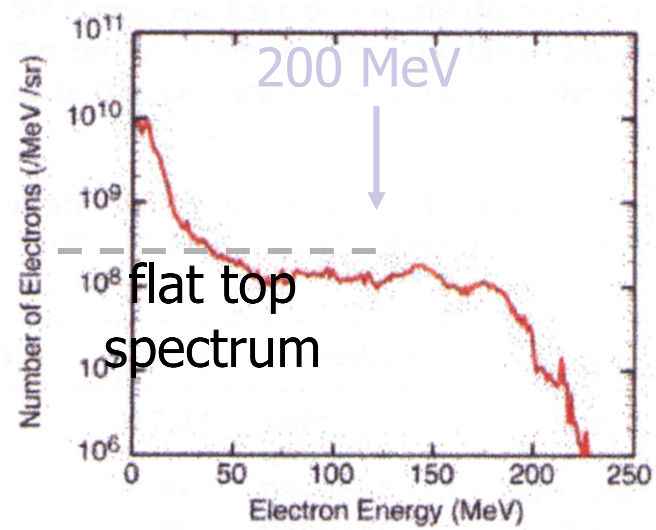
30 fs, 1J laser pulse

Electron Acceleration by a Wake Field Forced by an Intense Ultrashort Laser Pulse

V. Malka,[1*] S. Fritzler,[1] E. Lefebvre,[2] M.-M. Aleonard,[3] F. Burgy,[1] J.-P. Chambaret,[1] J.-F. Chemin,[3] K. Krushelnick,[4] G. Malka,[3] S. P. D. Mangles,[4] Z. Najmudin,[4] M. Pittman,[1] J.-P. Rousseau,[1] J.-N. Scheurer,[3] B. Walton,[4] A. E. Dangor[4]







Science 298, 1597 (2002)

Laser Wakefield Acceleration

Laser Plasma Interaction is a highly nonlinear problem especially for strong and short pulses. Understanding relies on numerical simulation:

Numerical Tool

What do we want to simulate?

High-Power Laser Pulse ionizes any material and forms a plasma

$\Rightarrow$ Classical, relativistic and highly nonlinear interaction of charged particles with EM-Radiation

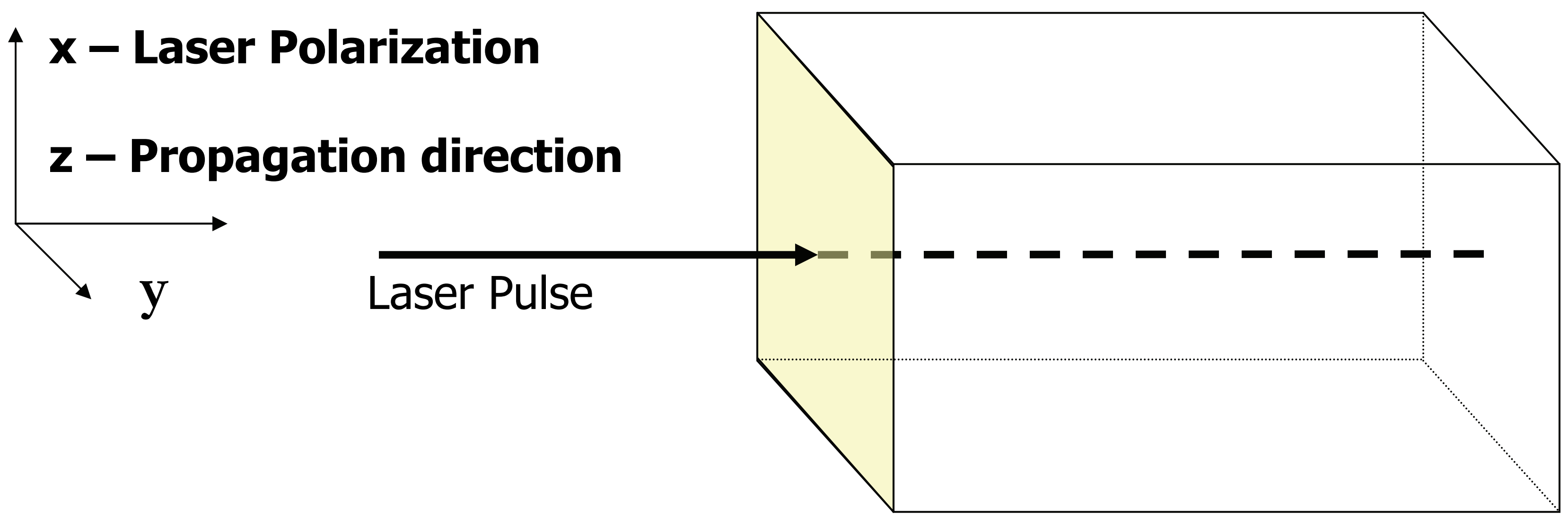
$\Rightarrow$particles move on a grid of EM-fields

Laser Wakefield Acceleration

Numerical Tool here:

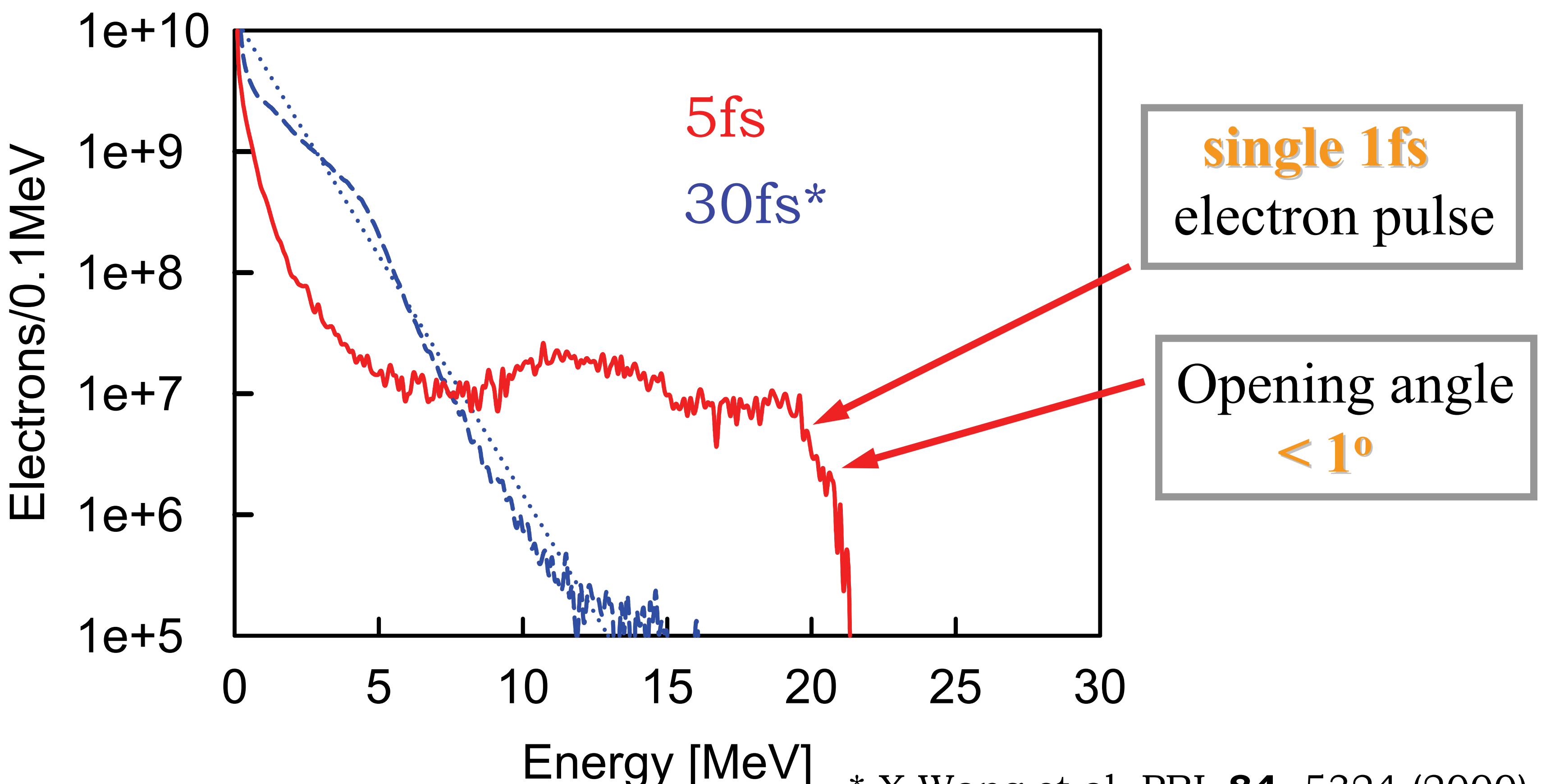
3D-PIC Code for Ideal Laser Matter Interaction

ILLUMINATION



Laser Wakefield Acceleration

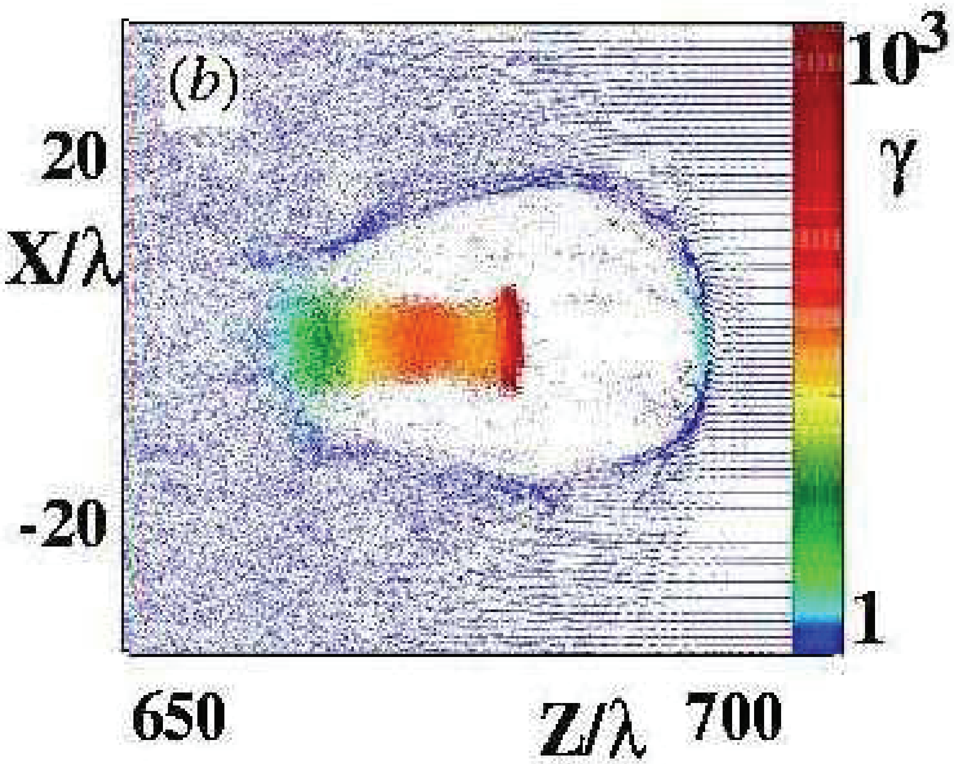
I_0=5x10^{18}W/cm^2, λ_p=8μm, w_0=5 μm, z = 100μm

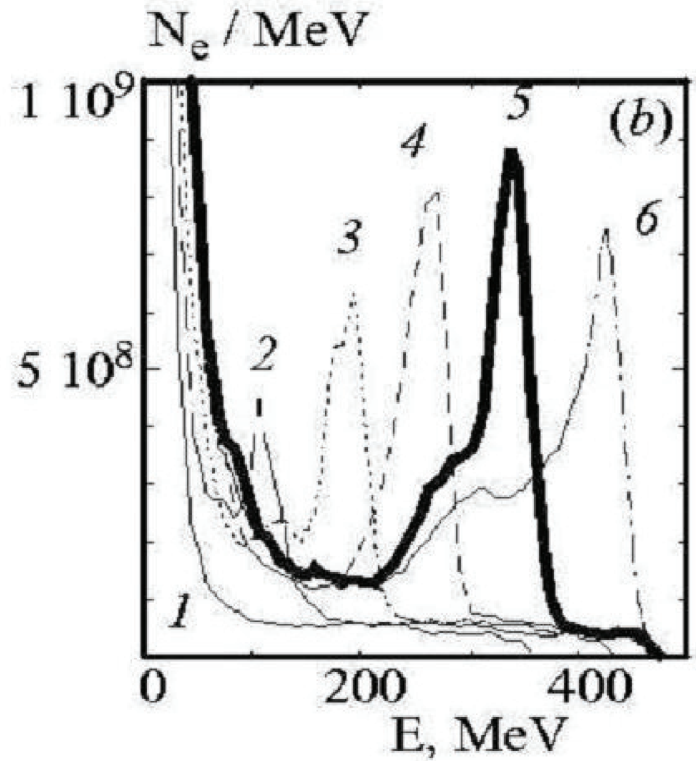


* X.Wang et.al. PRL **84**, 5324 (2000)

The Bubble Regime

12J, 33fs





A. Pukhov and J. Meyer-ter-Vehn Appl. Phys. B (March 2002)

The Bubble Regime

Here the effect relies on BREAKING the Plasma wave!

E.g. high density is perfered, hence short pulses are needed

THIS is the desired regime:

•Huge number of electrons in a highly localized pulse

•"monoenergetic"

•High conversion efficiency

•No injection, hence no synchronization

BUT:

Ultrashort (sub-10fs), high intensity (>10^{19}W/cm^2) pulses are needed

Precise control over a number of parameters

The Bubble Regime

Applications:

Electron diffraction

x-rays: FEL

Attosecond pump probe experiments

Aims:

Tuneable electron soure with respect to energy, energyspread, bunchlength and emittance

What you will see next

Simulations to reveal the physics of the bubble regime

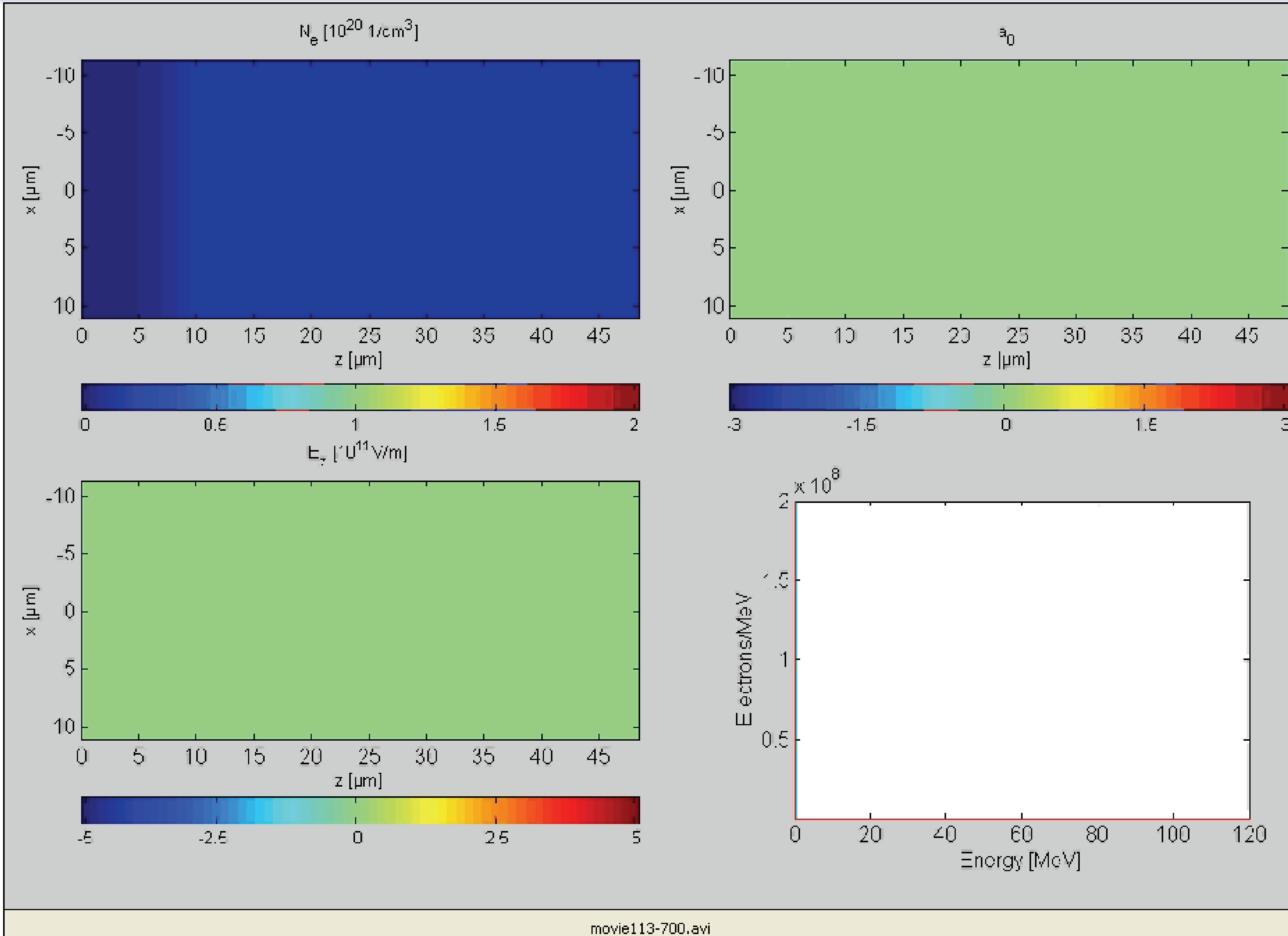
- Why are ultrashort laser pulses needed?
- Scaling of „bubble" properties

Comparing experiments with simulations

First: vary only the intensity. So fixed is: $5\,fs, w_0 = 5\mu m;\ \lambda_P = 8\mu m$

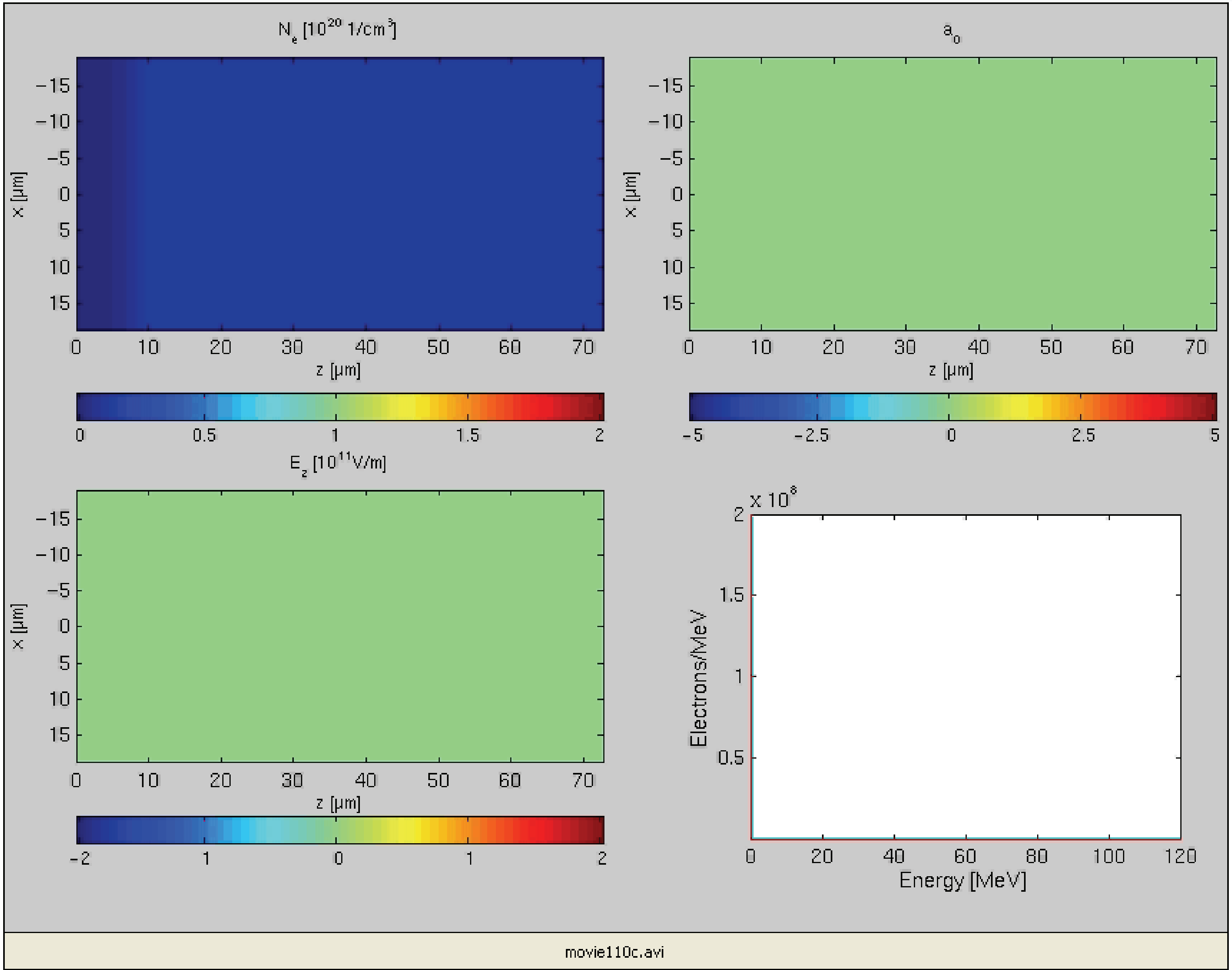
$a = 3;\ 2\cdot 10^{19}\ W/cm^2$	$a < a_{wb}$	$a_{wb} = 4.36$
$a = 5;\ 5.5\cdot 10^{19}\ W/cm^2$	$a > a_{wb}$	
$a = 10; 2.2\cdot 10^{20}\ W/cm^2$		
$a = 30; 2\cdot 10^{21}\ W/cm^2$		

5fs, a=3



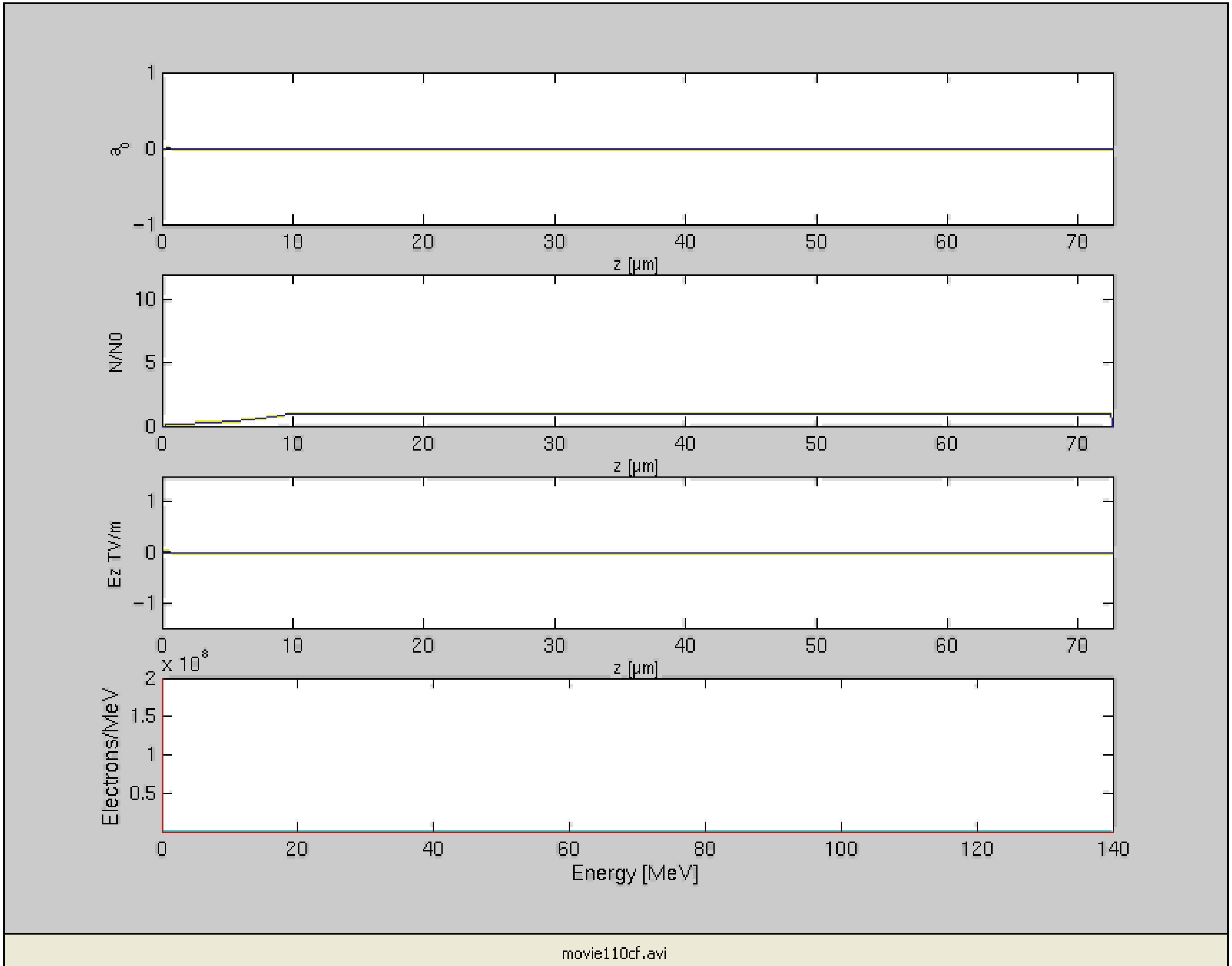
N_e [10^20 1/cm^3]
a_0
x [μm]
z [μm]
-10
-5
0
5
10
0
5
10
15
20
25
30
35
40
45
0
0.5
1
1.5
2
-3
-1.5
0
1.5
3
-5
-2.5
0
2.5
5
x 10^8
2
1
0.5
0
20
40
60
80
100
120
Energy [MeV]
movie113-700.avi

5fs, a=5



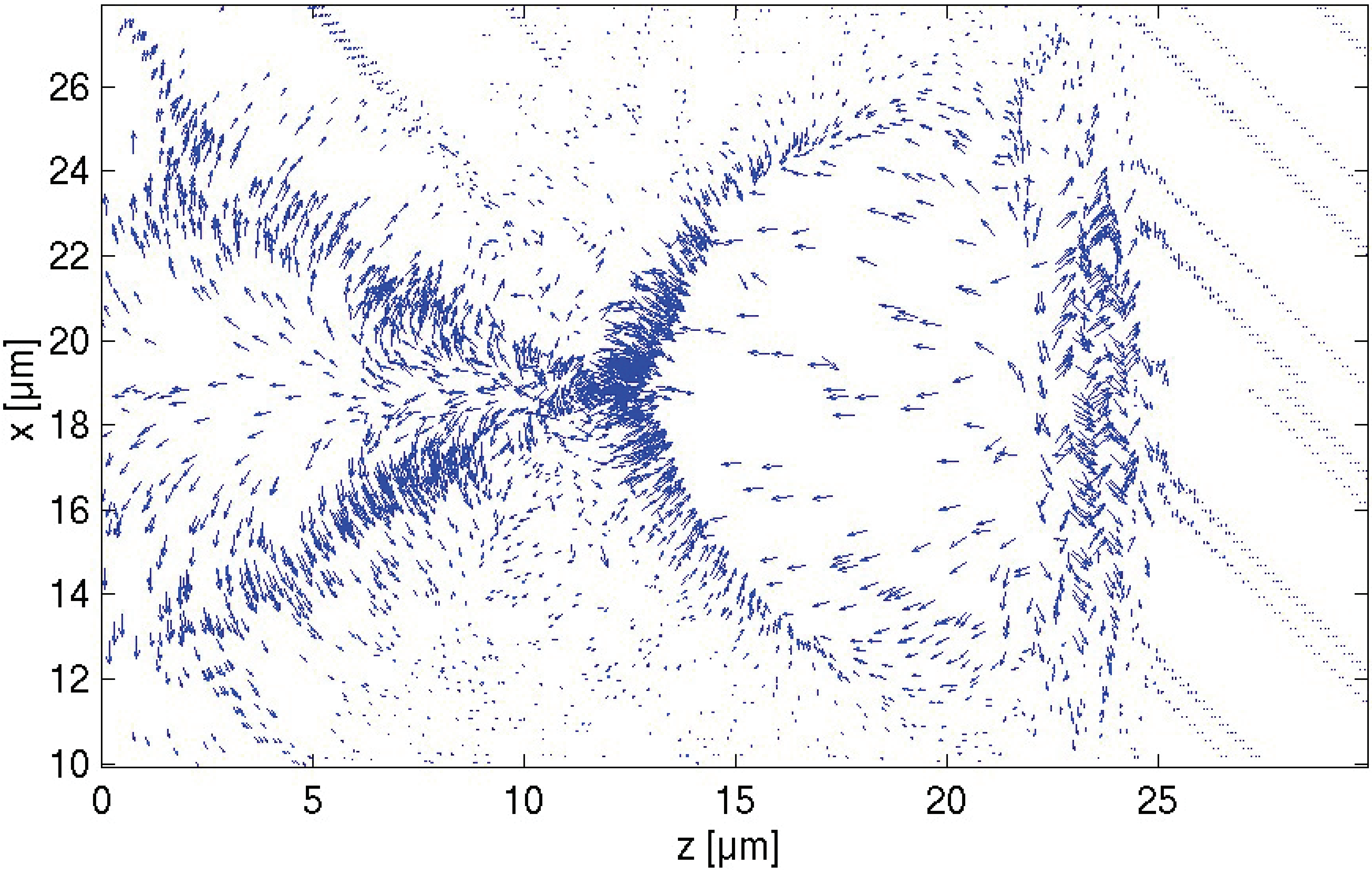
N_e [10^20 1/cm^3]
a_0
x [μm]
z [μm]
−15
−10
−5
0
5
10
15
0
10
20
30
40
50
60
70
0
0.5
1
1.5
2
−5
−2.5
0
2.5
5
E_z [10^11 V/m]
−2
1
0
1
2
x 10^8
Electrons/MeV
Energy [MeV]
0
20
40
60
80
100
120
0.5
1
1.5
2
movie110c.avi

5fs, a=5

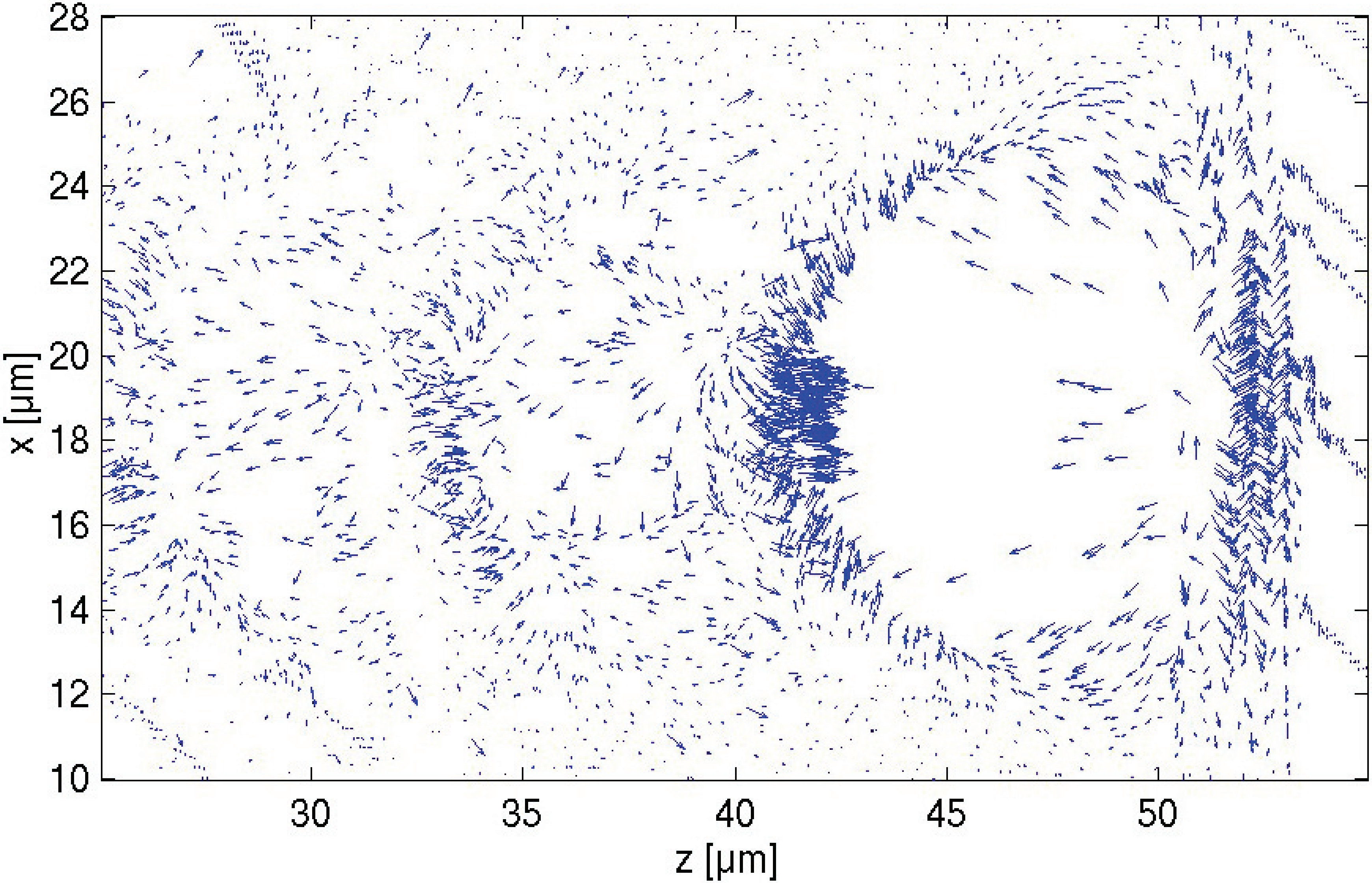


a0
1
0
-1
0 10 20 30 40 50 60 70
z [μm]
N/N0
10
5
0
z [μm]
Ez TV/m
z [μm]
x 10^8
Electrons/MeV
2
1.5
1
0.5
0 20 40 60 80 100 120 140
Energy [MeV]
movie110cf.avi

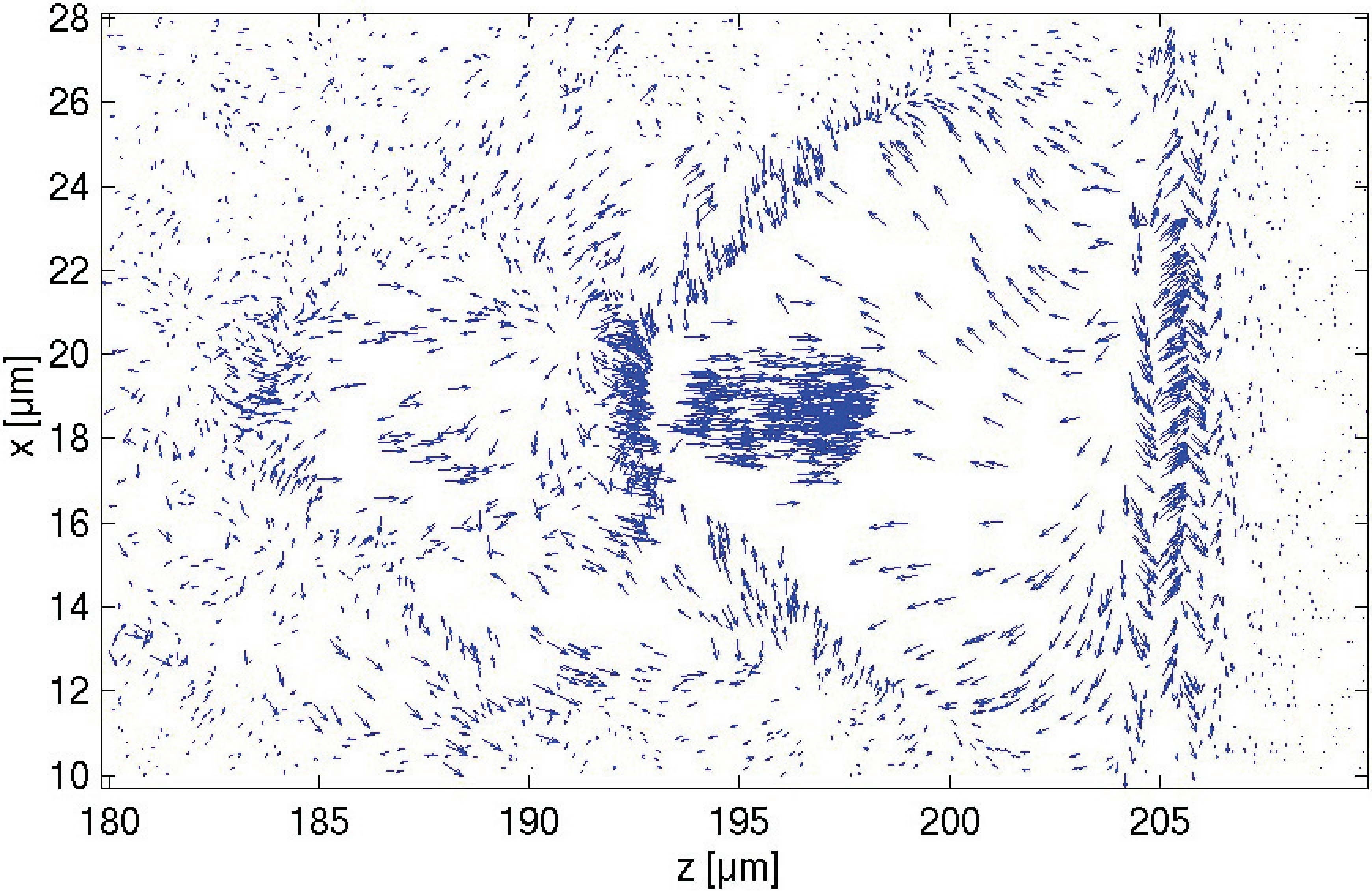
5fs, a=5



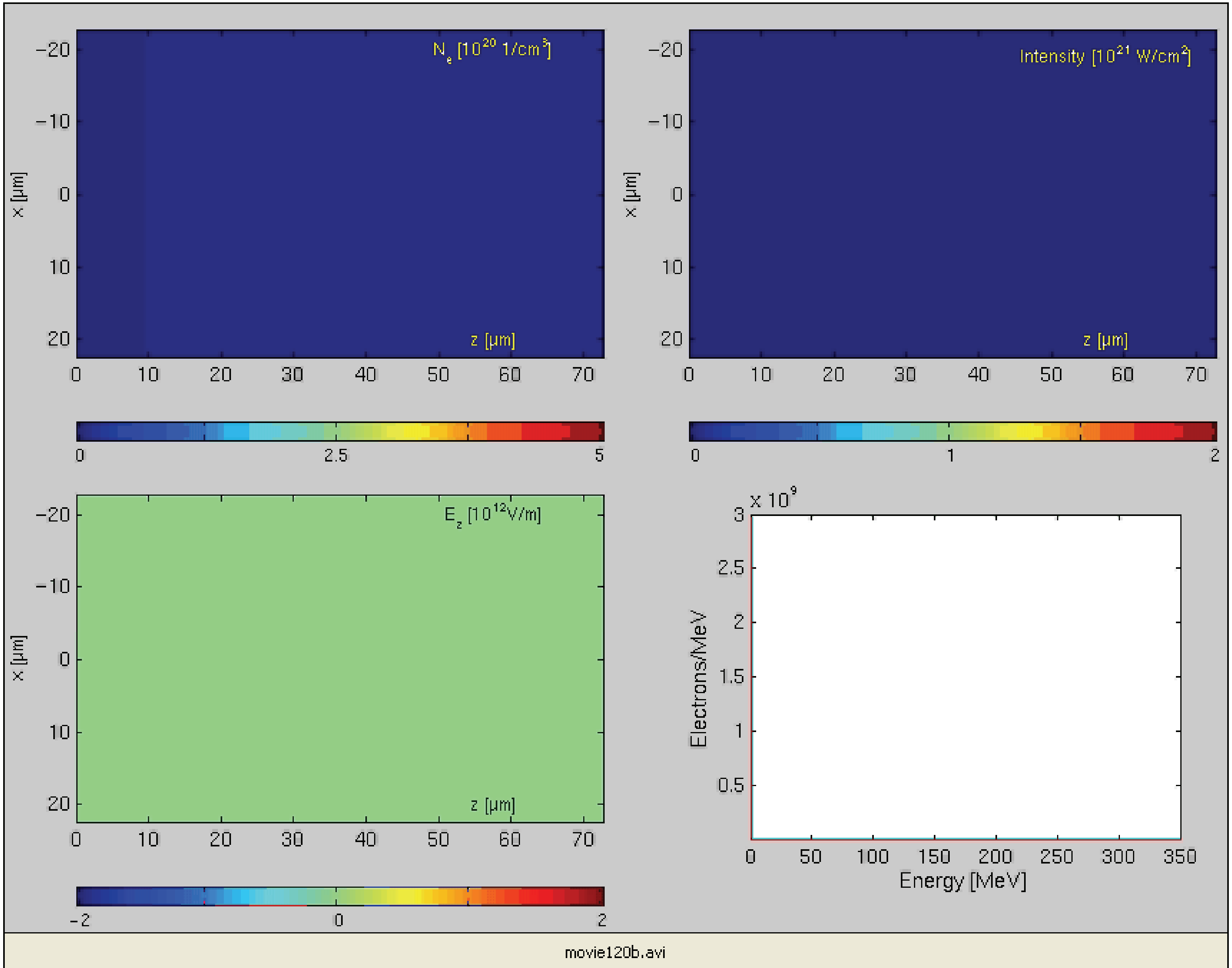
5fs, a=5



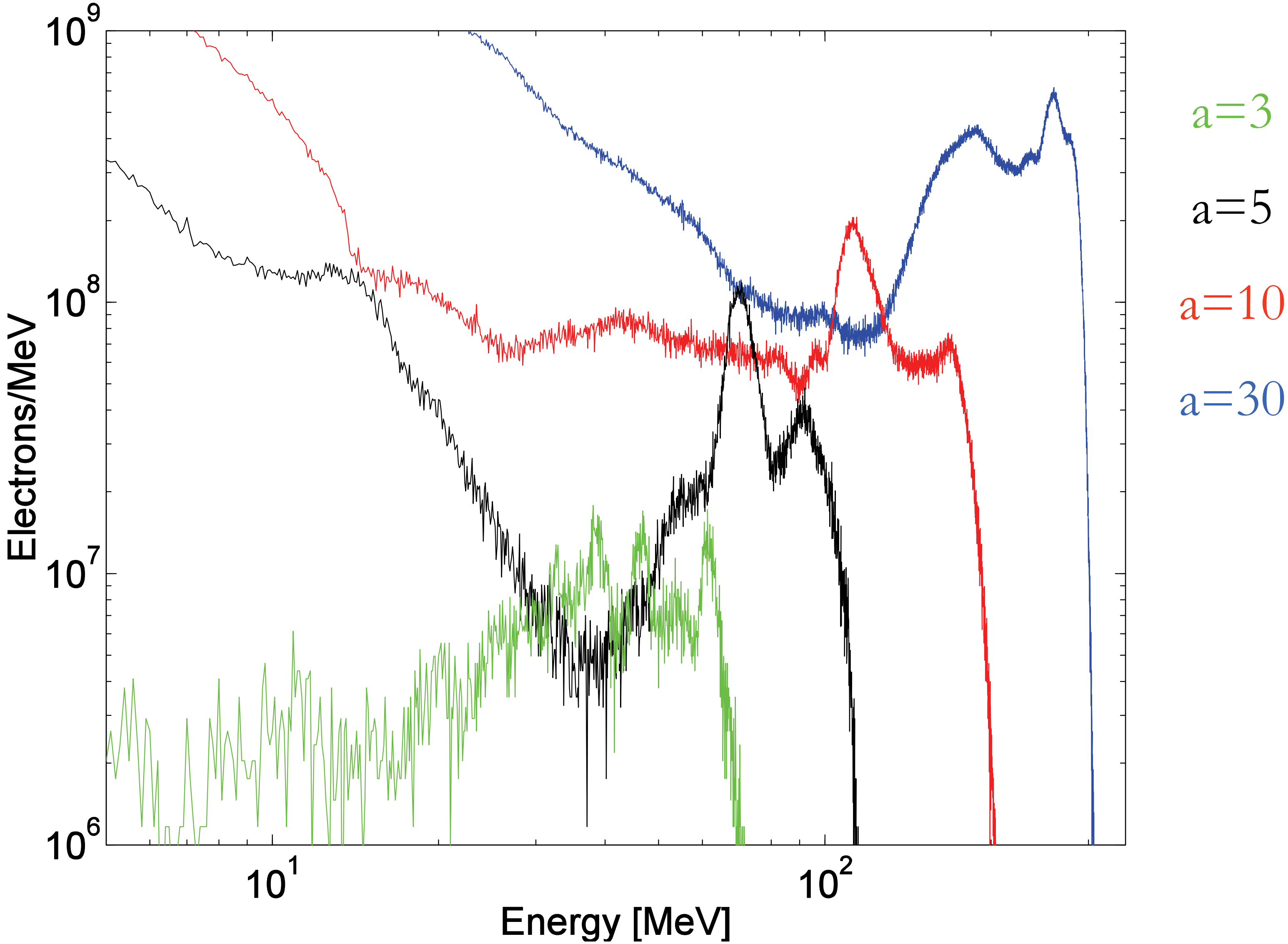
5fs, a=5



5fs, a=30, 777TW



5fs Summary



5fs Summary

Condition to form a stable bubble

$$a > a_{wb} \quad L_L < \lambda_p \quad \lambda_p < 2R_b < 6\lambda_p \quad R_b = w_0 \cdot a^{0.25}$$

$R_b \sim E_{acc} \sim a^{0.25}$ => acceleration is limited => multistages

Short lifetime of the bubble (~200-400µm)

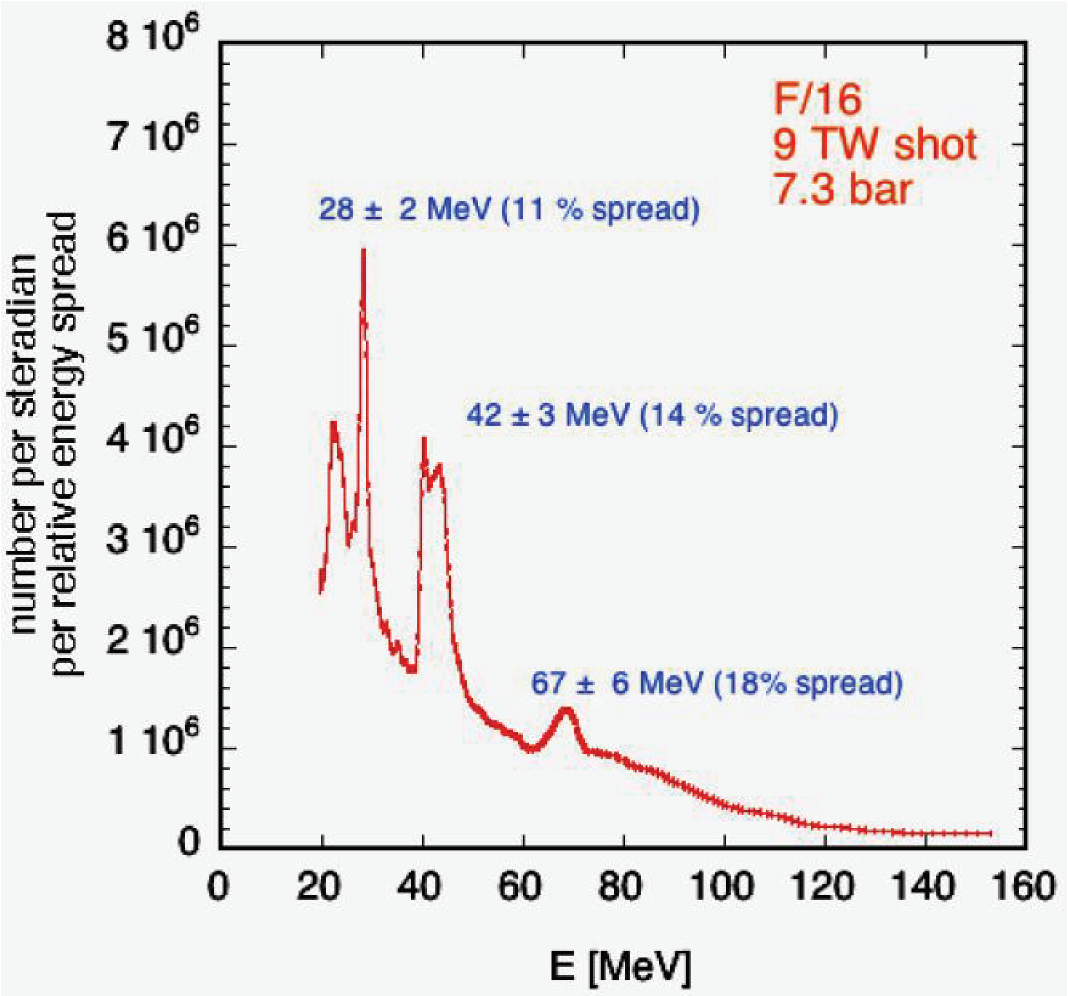
Density profile changes electron bunch properties

Conditions out of reach for present laser systems => but

Experiments

360mJ, $1.2\text{x}10^{18}\text{W/cm}^2$,

$$40\,fs, \lambda_P = 8\mu m, \Rightarrow L_L \approx \lambda_p$$

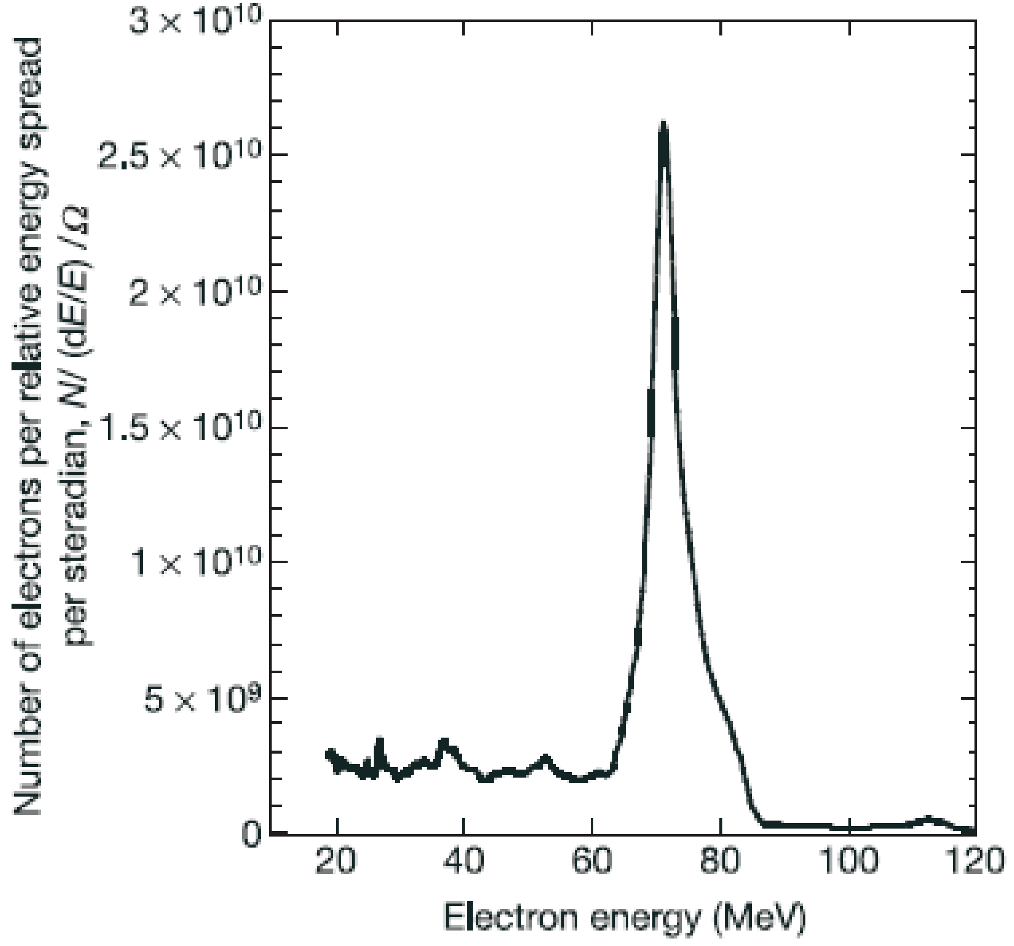


CCLRC Data, Kyoto (2004)

Experiments

500mJ, 2.5×10^{18}W/cm^2,

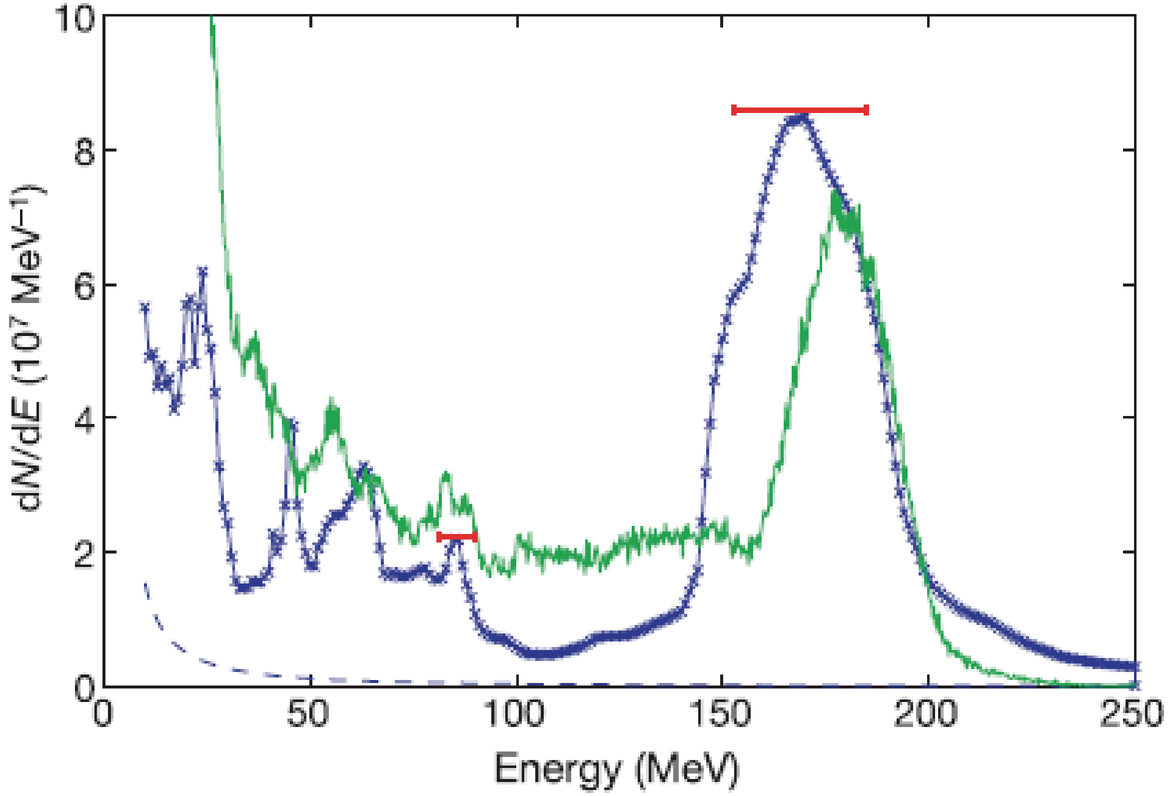
$$40\, fs, \lambda_P = 8\mu m, \Rightarrow L_L \approx \lambda_p$$



Mangles et.al, Nature **431**, 535 (2004)

Experiments

$$30\,fs, 1J, 3.2\cdot 10^{18}\,W/cm^2, \lambda_P = 13.6\mu m$$

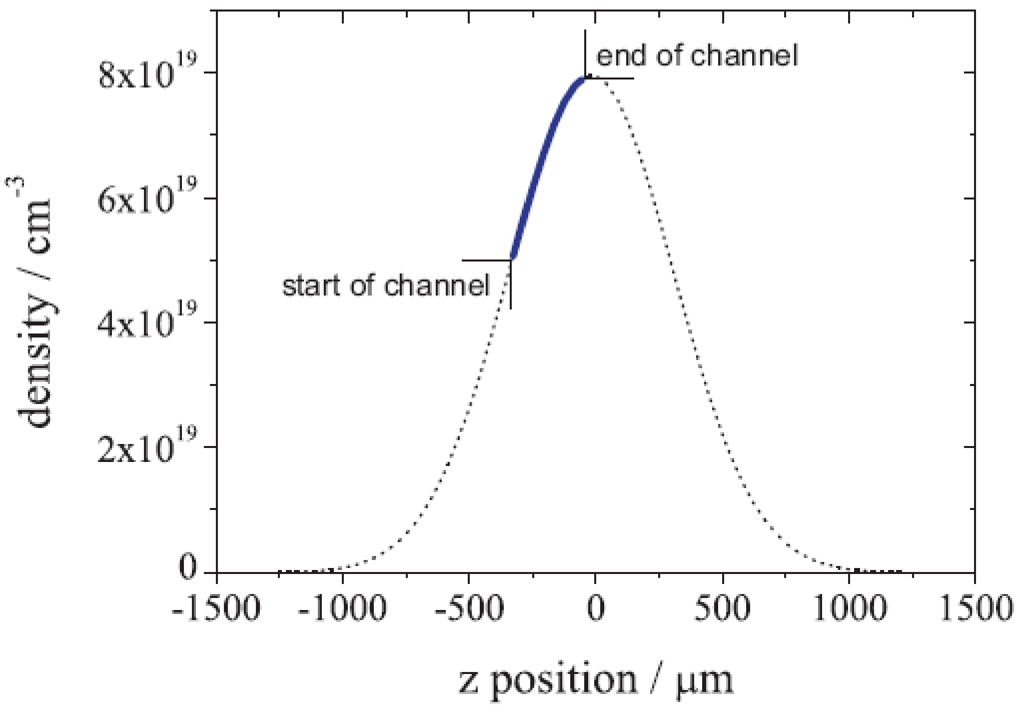


Faure et.al, Nature **431**, 541 (2004)

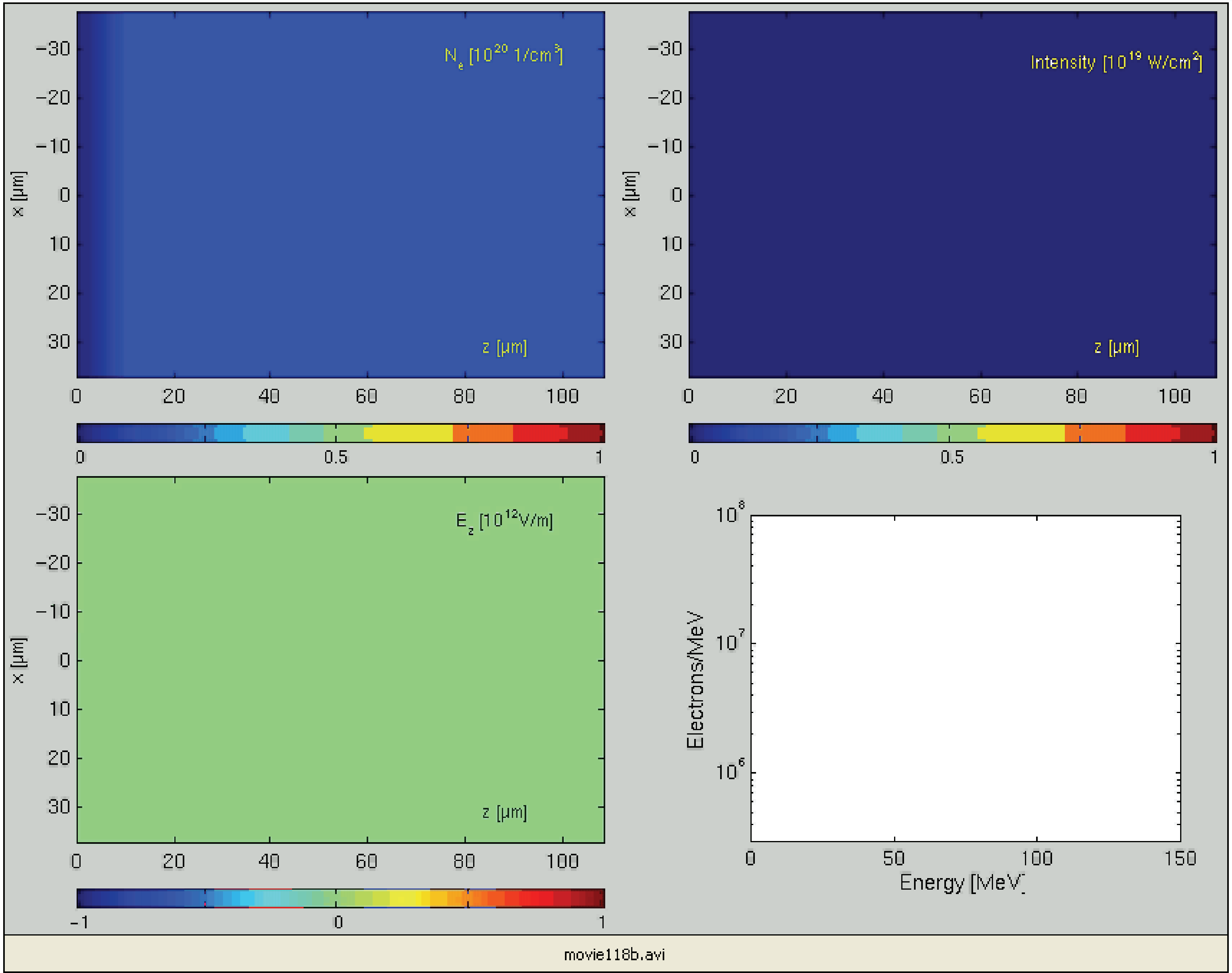
Simulate Experiments

Setup of the Rutherford ASTRA: $1.3*10^{18}W/cm^2$, 40fs

Setup of the Jena Experiment: $2*10^{19}W/cm^2$, 80fs & 40fs

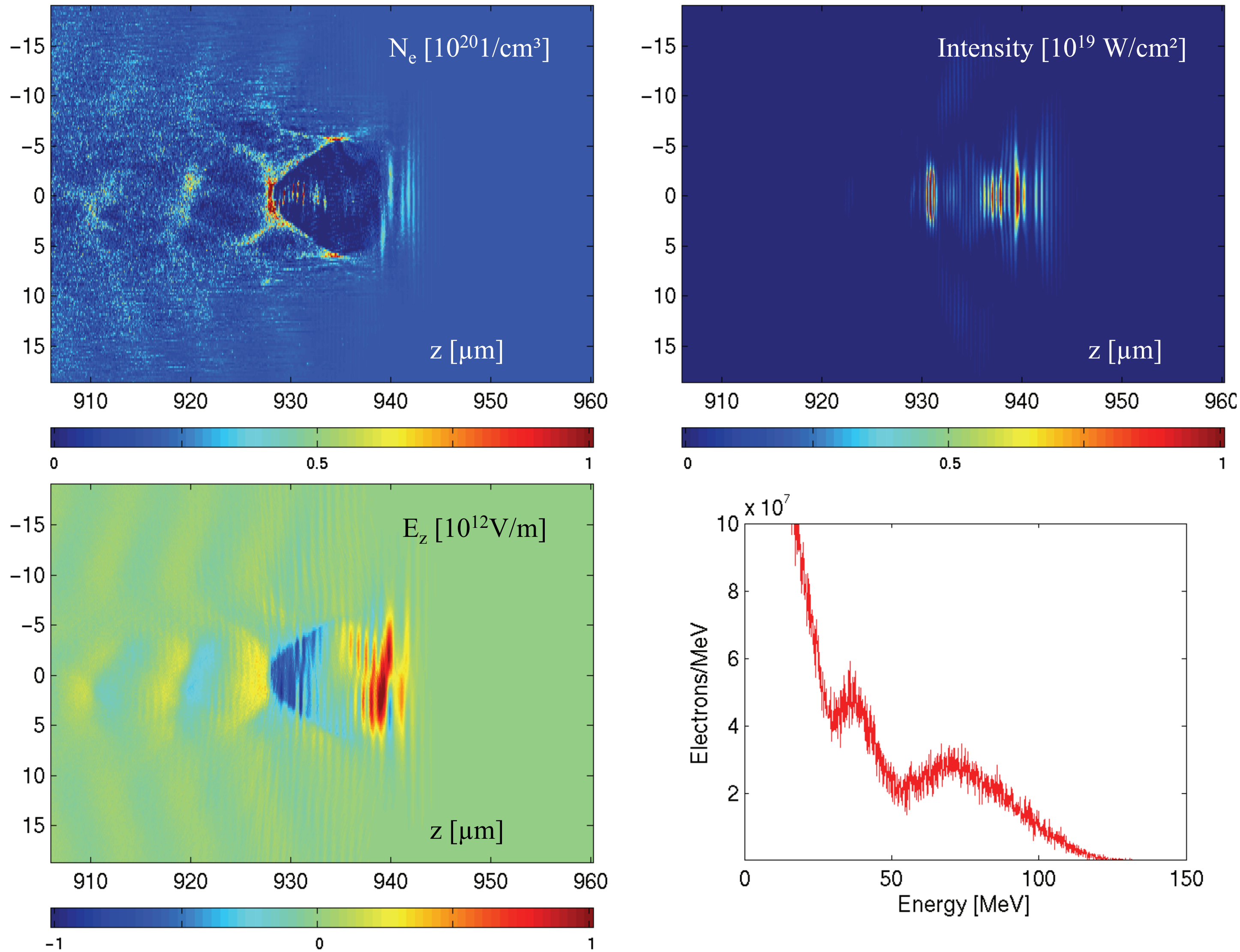


40fs, a=0.767, 390mJ

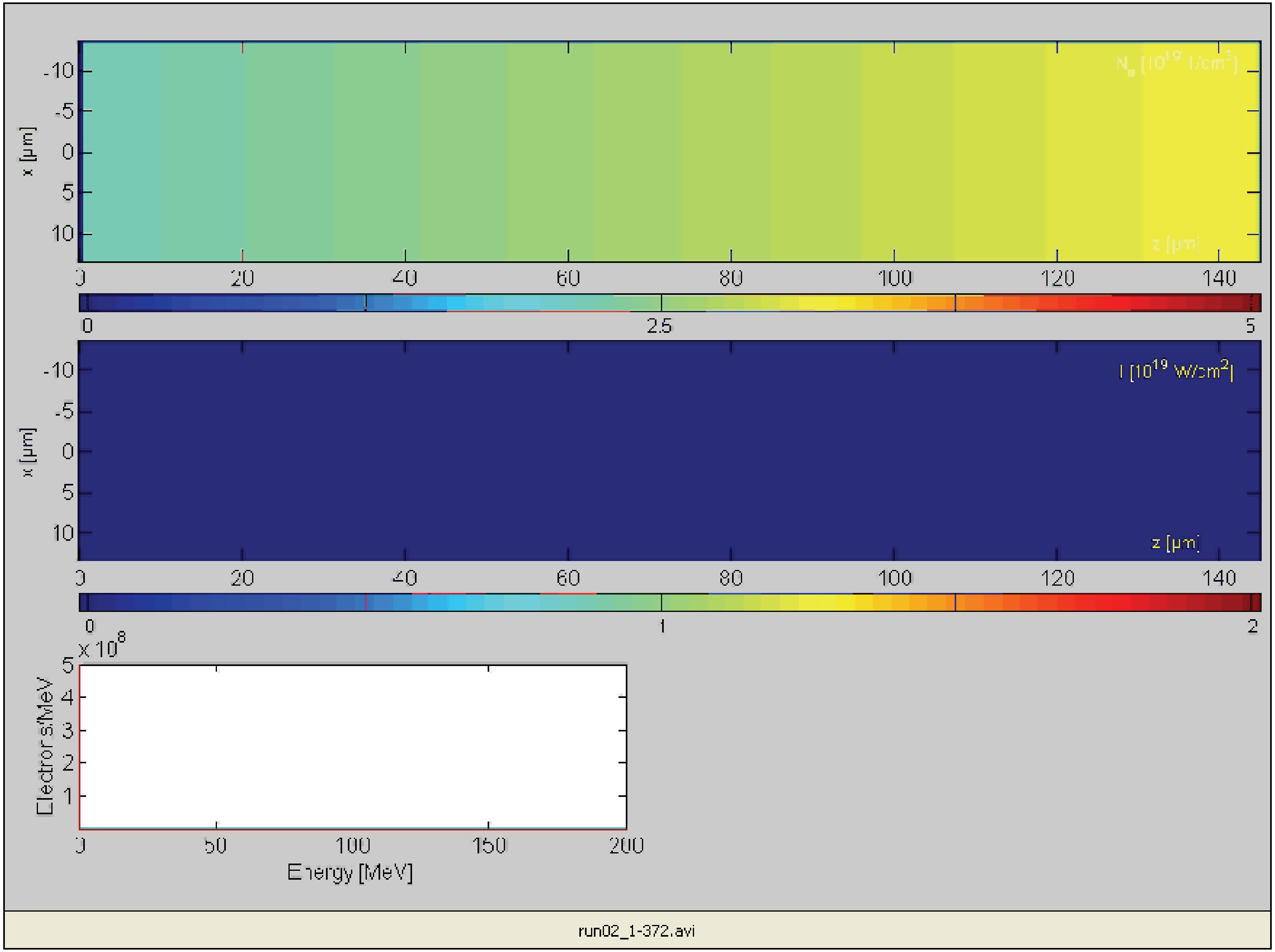


40fs

$a = 0.767; 1.3\cdot 10^{18}\, W/cm^2; 390mJ, \lambda_P = 8\mu m \qquad L_L \approx \lambda_p \qquad a < a_{wb}$

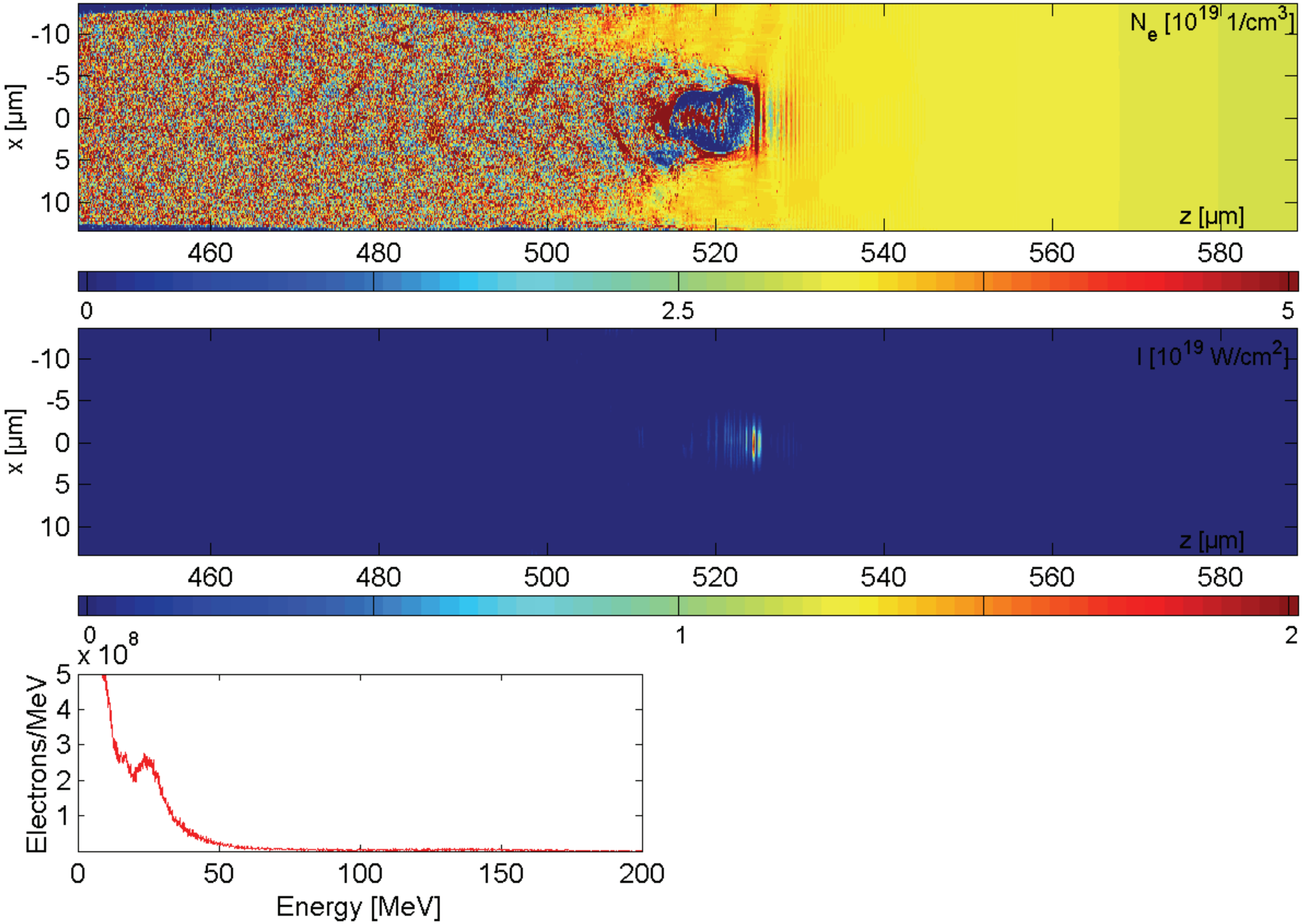


80fs, a=3



x [µm]
-10
-5
0
5
10
N_e [10^19 1/cm^3]
z [µm]
0
20
40
60
80
100
120
140
0
2.5
5
I [10^19 W/cm^2]
1
2
x 10^8
Electrons/MeV
Energy [MeV]
50
150
200
run02_1-372.avi

80fs, a=3



N_e [10^19 1/cm^3]
x [µm]
-10
-5
0
5
10
z [µm]
460
480
500
520
540
560
580
0
2.5
5
I [10^19 W/cm^2]
x [µm]
z [µm]
0
1
2
x 10^8
Electrons/MeV
Energy [MeV]
0
50
100
150
200

Summary of second part

New Acceleration Regime (bubble regime)

Unique beam properties: ~10fs, ~1nC, 10^9 Electrons, Divergence ~1°

High conversion efficiency: ~20-35%

Benefits from sub-10fs pulses:
Tuneable electron source (between 10 and 300MeV)
by warying Power/Intensity/Focus/Gas density & Length

Stable in operation

Precise control of gas density and length is necessary