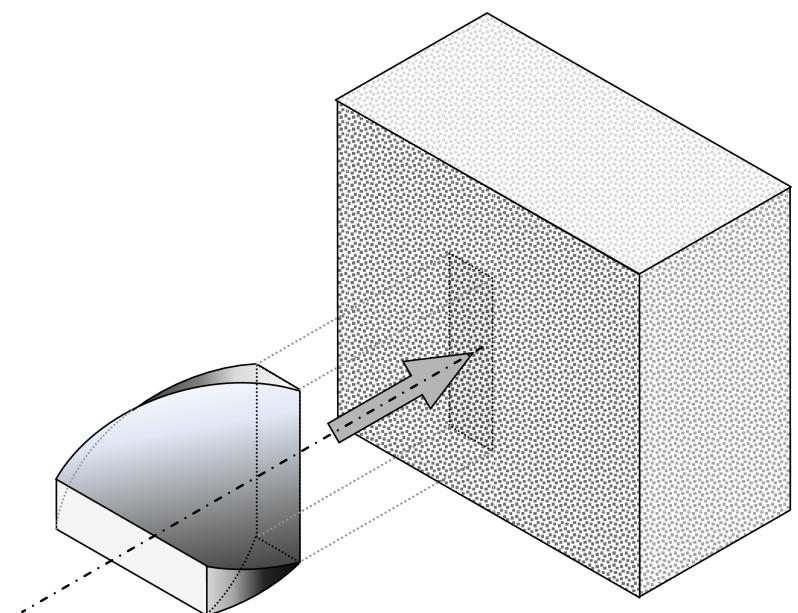
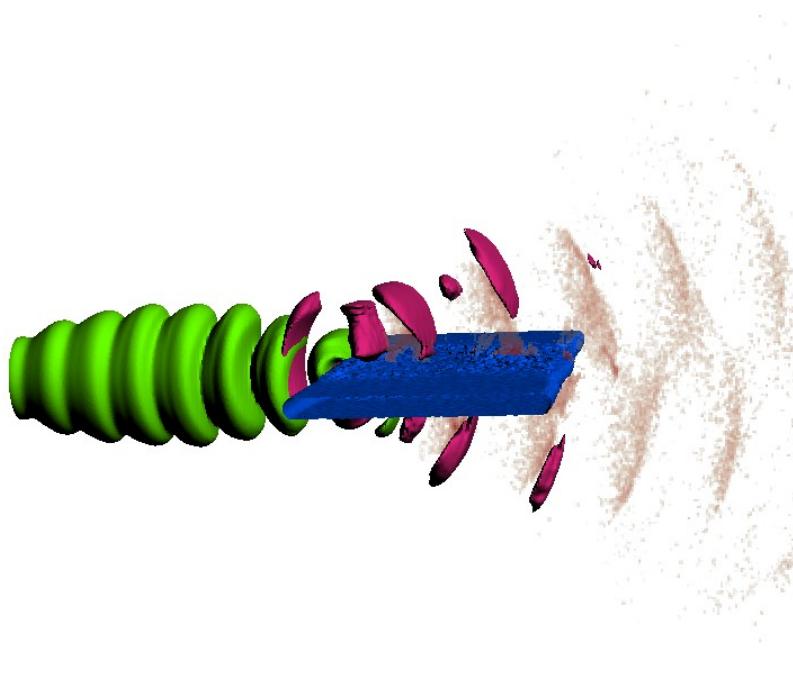


Interaction of plasmas with intense laser pulses carrying orbital angular momentum

Zsolt Lecz, Alexander Andreev, Andrei Seryi, Ivan Konoplev



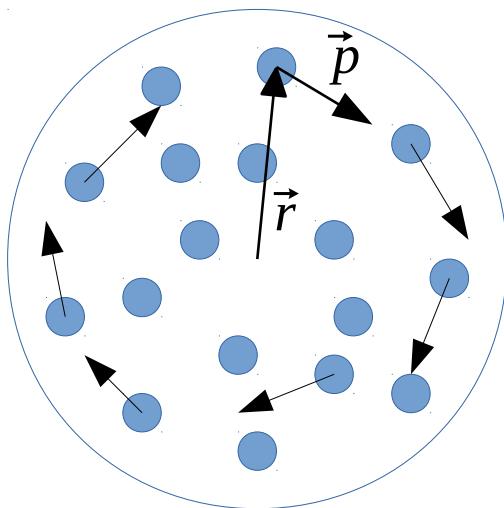
John Adams Institute for Accelerator Science Lecture Series
14.04.2016

Content

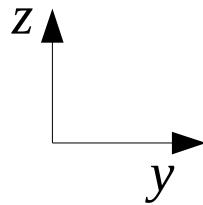
- Introduction, motivation
- Circularly polarized (CP) intense pulse interacting with solid density targets
 - Laser induced Coherent Synchrotron Emission (CSE)
 - Attopulse and attospiral generation
- Screw-shaped pulses interacting with underdense plasmas
 - Generation of GigaGauss axial magnetic fields
 - Possible applications in LWFA

Orbital Angular Momentum (OAM)

Particles

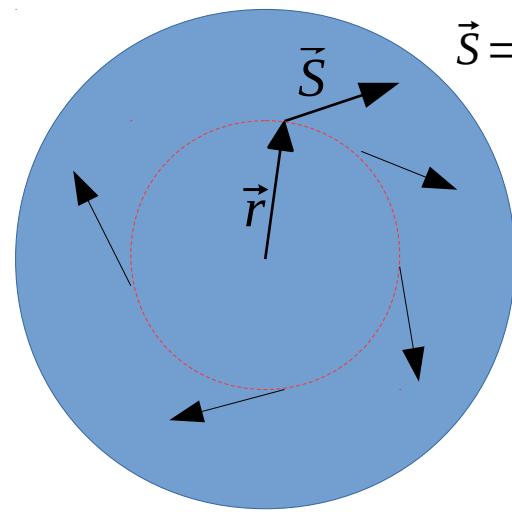


$$r = \sqrt{y^2 + z^2}$$



$$L_{ix}(t_e) = \sum_j (\mathbf{r}_j \times \mathbf{p}_j)_x,$$

EM Waves

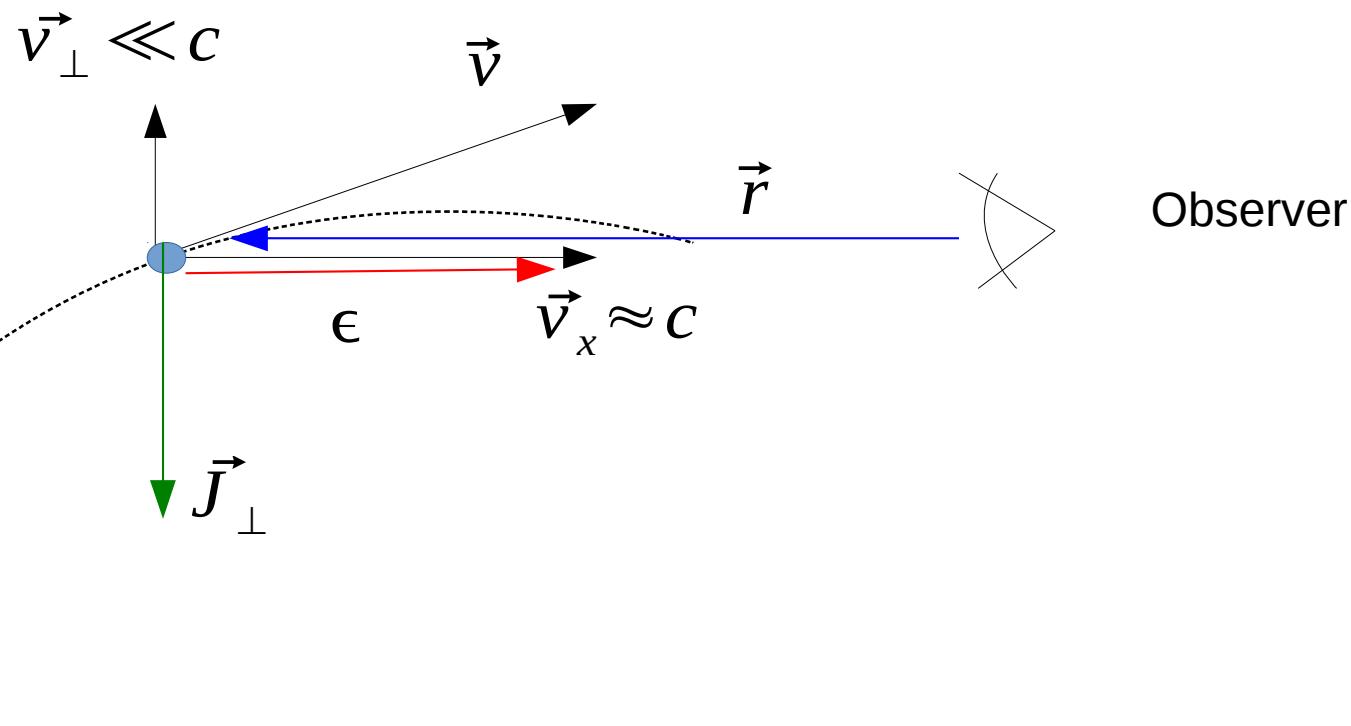


$$\vec{S} = \frac{(\vec{E} \times \vec{B})}{\mu_0}$$

$$L_{Lx}(x_0, x_1) = \frac{1}{c^2} \int_{x_0}^{x_1} \int_0^{2y_0} \int_0^{2z_0} (\mathbf{r} \times \mathbf{S})_x dz dy dx,$$

Synchrotron radiation

$$I(\omega) \sim \left| \int dt \vec{\epsilon} \times [\vec{\epsilon} \times J(\vec{r}, t)] \exp[i\omega(t - \vec{\epsilon} \cdot \vec{r}/c)] \right|^2 \quad \xrightarrow{\text{blue arrow}} \quad I(\omega) \sim |J_{\perp}(x, t) \exp[i\omega(t - x(t)/c)]|^2$$



Synchrotron radiation

$$I(\omega) \sim \left| \int dt \vec{\epsilon} \times [\vec{\epsilon} \times J(\vec{r}, t)] \exp[i\omega(t - \vec{\epsilon} \cdot \vec{r}/c)] \right|^2$$



$$I(\omega) \sim |J_{\perp}(x, t) \exp[i\omega(t - x(t)/c)]|^2$$

$$x(t) = r(t) = ?$$

$$\vec{v}_{\perp} \ll c$$

$$\vec{v}$$

$$\vec{r}$$

$$\gamma = (1 - \dot{x}(t)^2/c^2)^{-1/2}$$

Observer

$$\epsilon$$

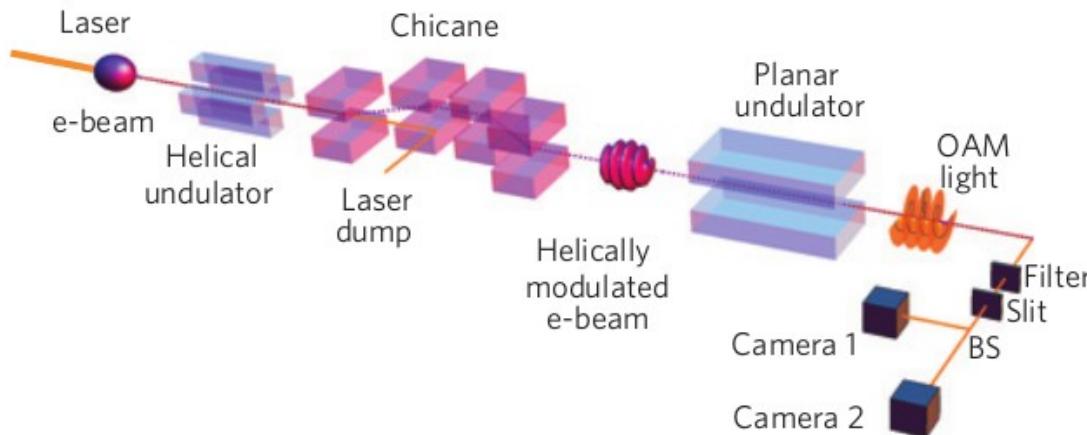
$$\vec{v}_x \approx c$$

$$\ddot{x}(t) \sim t^{2n-1} \Rightarrow \omega_r \sim \gamma^{\frac{2n+1}{n}}$$

$$I(\omega) \sim \omega^{-\frac{2n+2}{2n+1}}$$

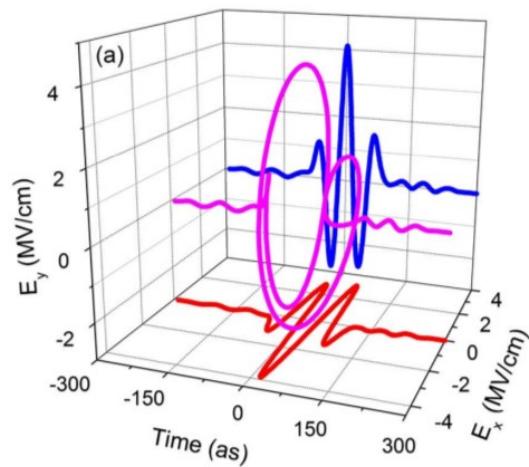
D. an der Brügge and A. Pukhov, arxiv:1111.4133 (2011)

Twisted pulses (using electron beams)

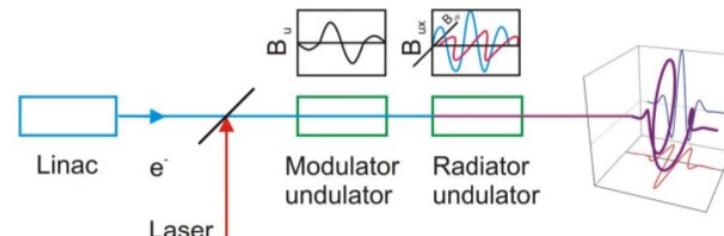


Erik Hemsing et al., Nature Physics **9**, 549 (2013)

Electron gamma:
100-1000
Undulator length:
~cm-m



Gy. Toth et al., Optics Letters **40**, 4317 (2015)



Simulation setup: Solid density target, CP pulse

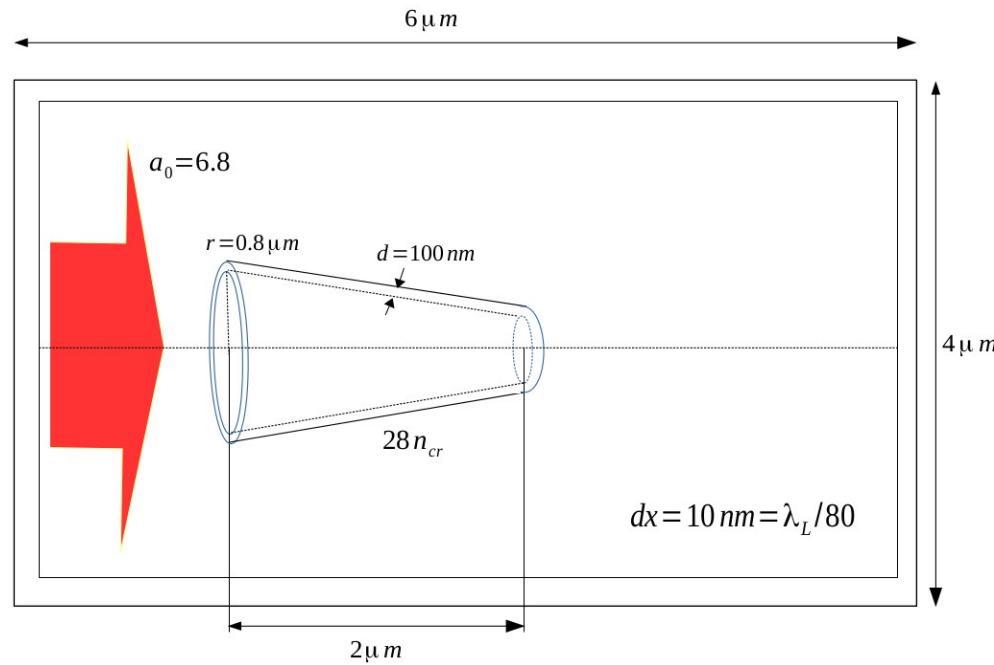
Codes:

- ✓ Vsim (VORPAL), Tech-X Corp.
- ✓ EPOCH

Collisionless, relativistic particle-in-cell plasma simulations.

Normalized laser amplitude

$$a_0 = \sqrt{\frac{I [W/cm^2] \lambda_L^2 [\mu m]}{1.4 \times 10^{18}}}$$



CP pulse vs. flat foil

Zs. Lécz et al., LPB **34**, p. 31-42 (2016)

Simulation parameters:

$$I_L = 10^{20} \text{ W/cm}^2$$

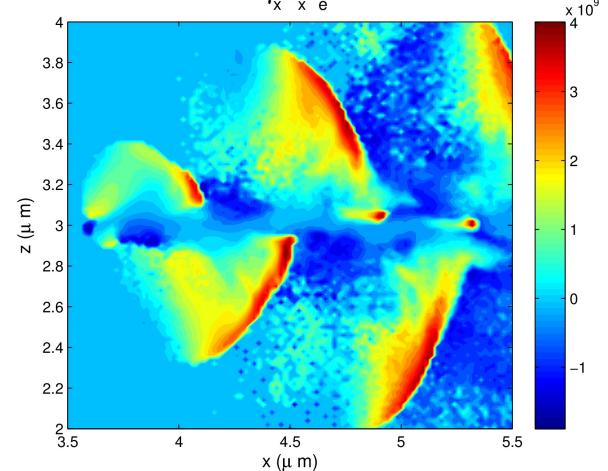
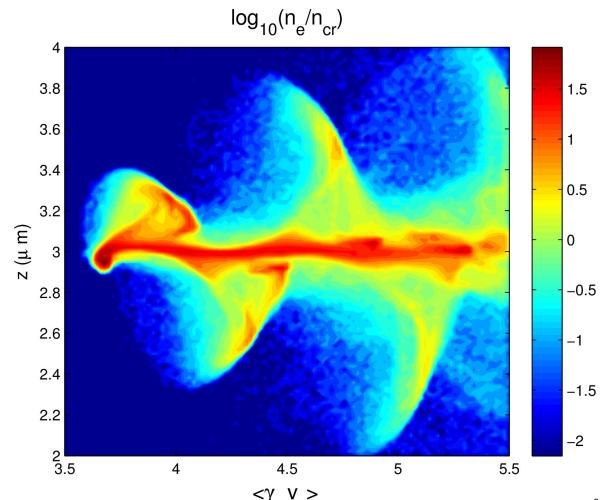
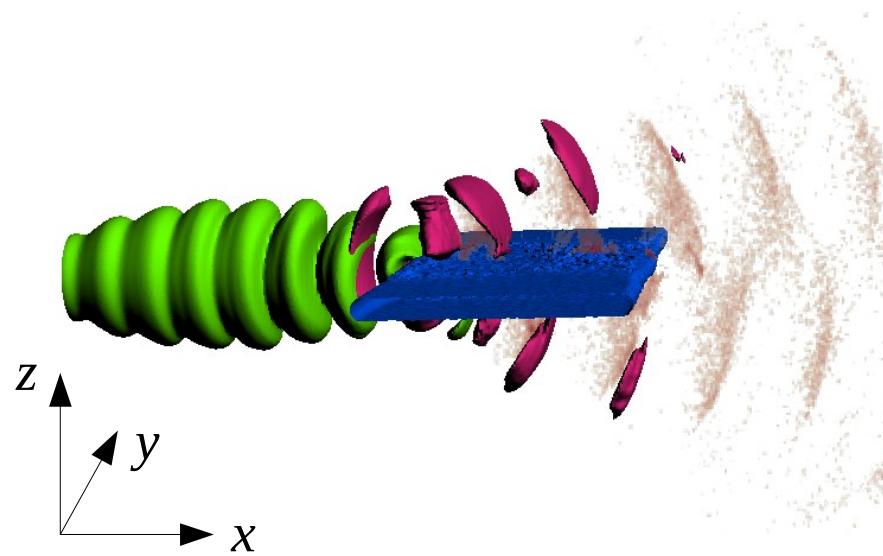
$$h = 0.2 \mu\text{m}$$

$$t_L = 20 \text{ fs}$$

$$n_0 = 28 n_{cr}$$

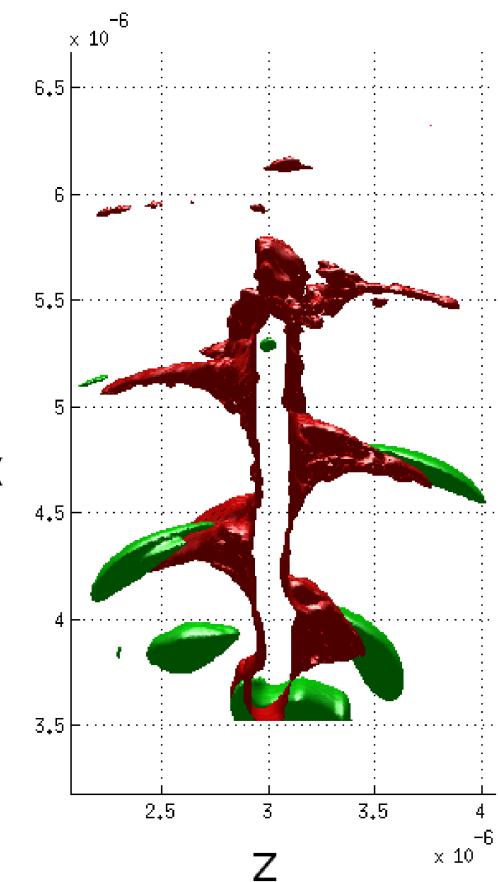
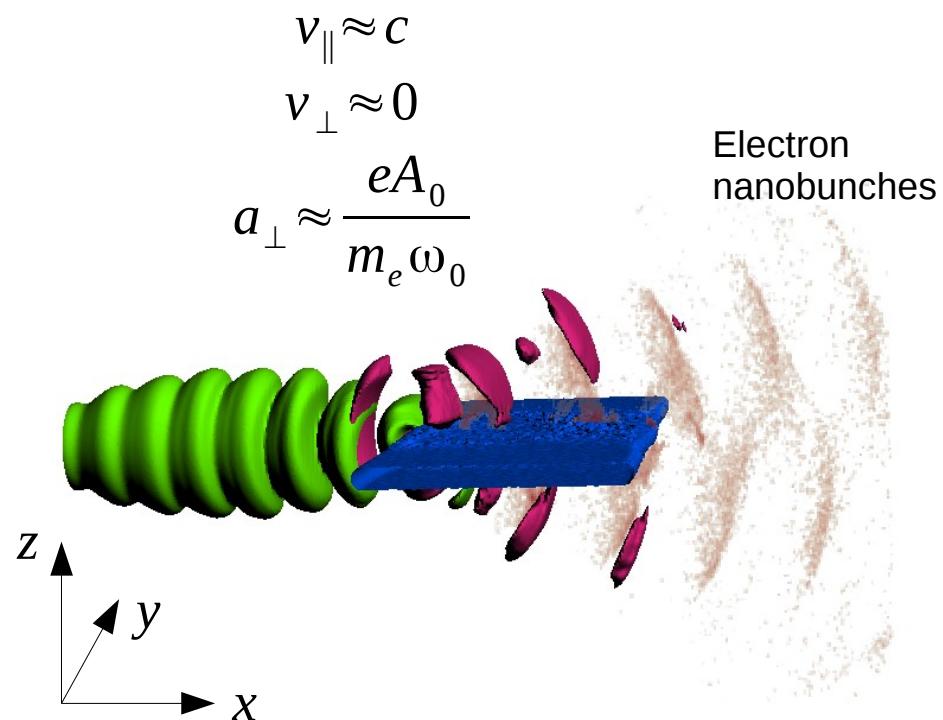
$$w_L = 2 \mu\text{m}$$

solid hydrogen foil



Attopulse generation

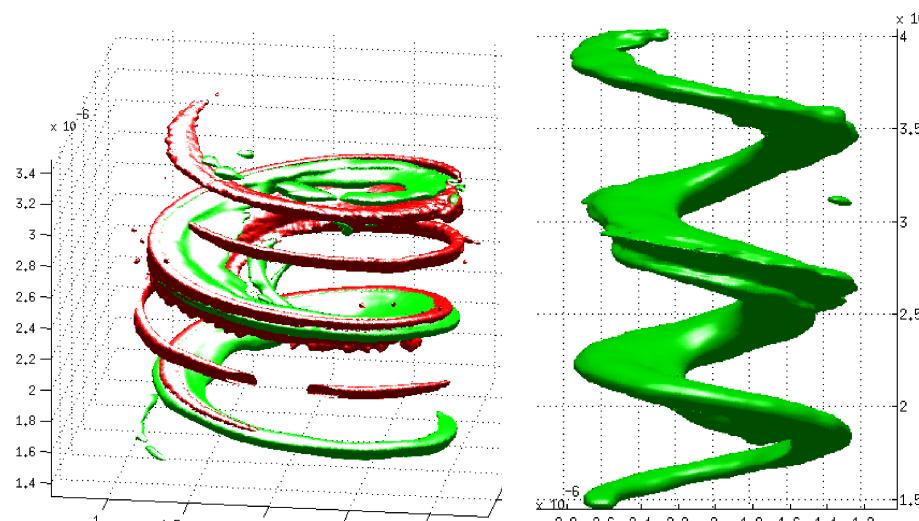
Relativistic electrons near the plasma surface emit coherent radiation.



Rotation symmetric interaction: CP pulse vs. cone-like targets

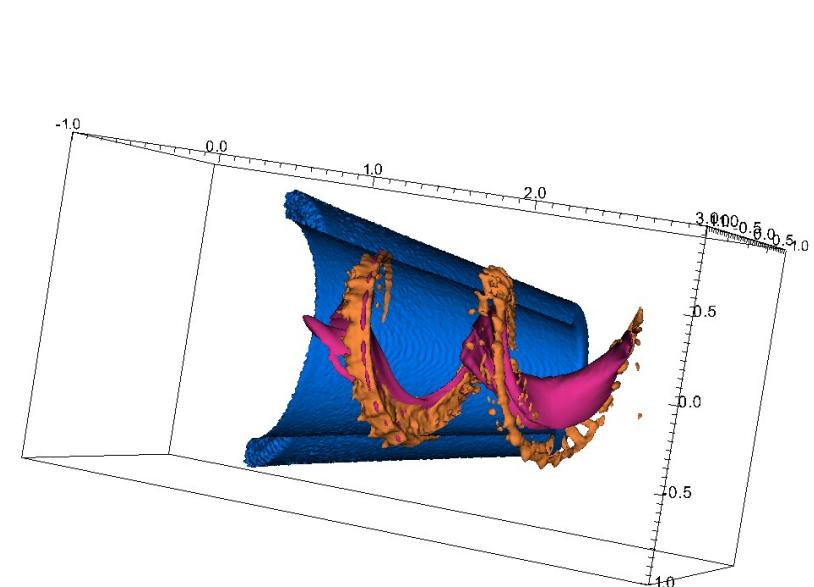
Cylinder target

Energetic electrons move on
a spiral path



Cone target

Focusing of attospiral near
the exit hole

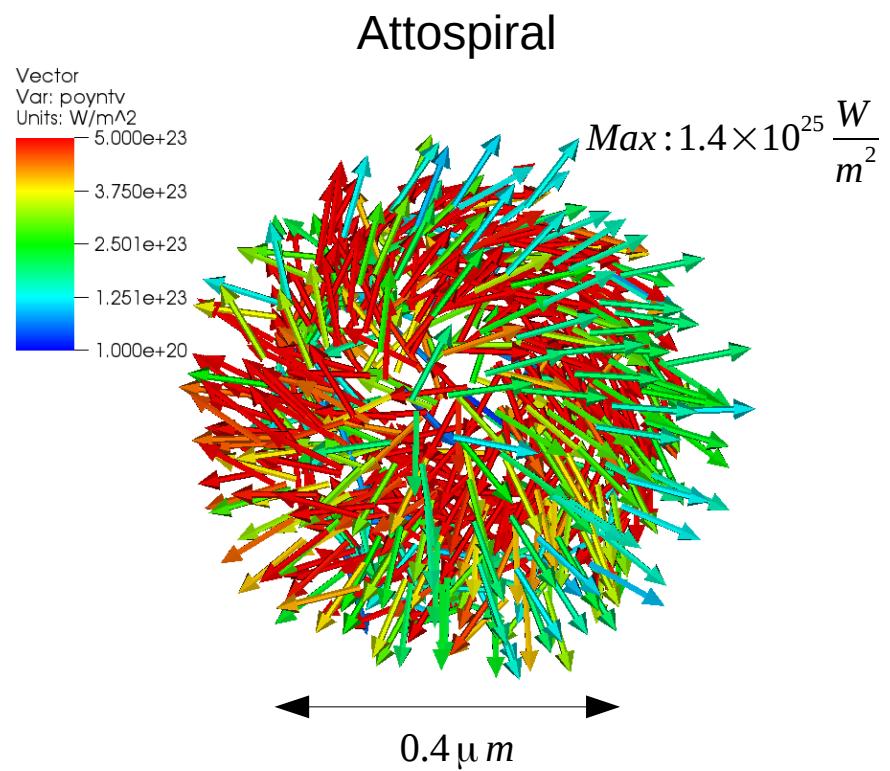
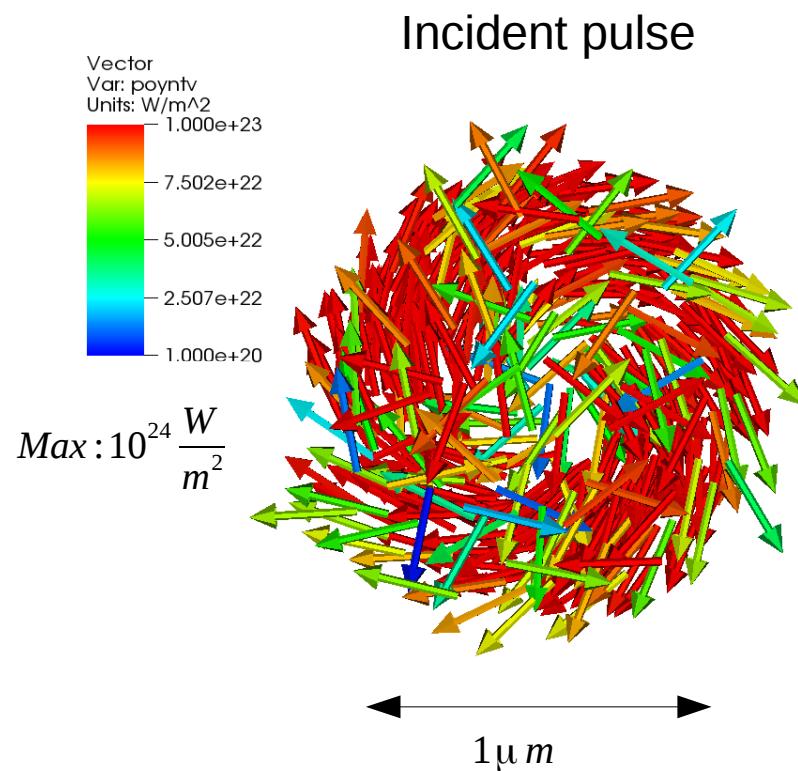


Movie

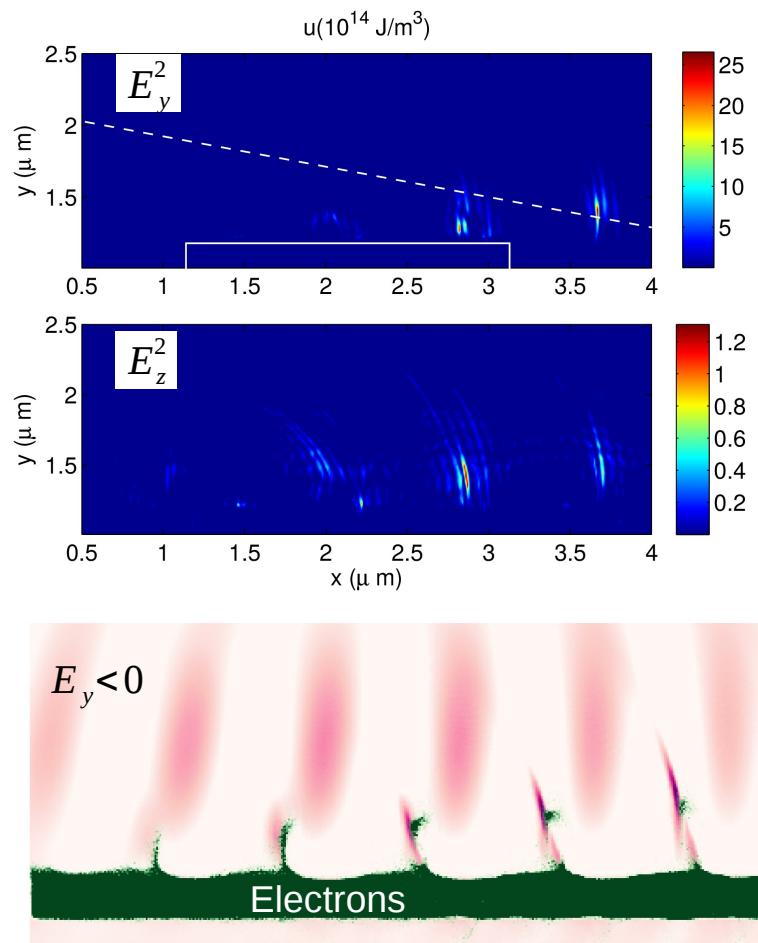


OAM in attopulse

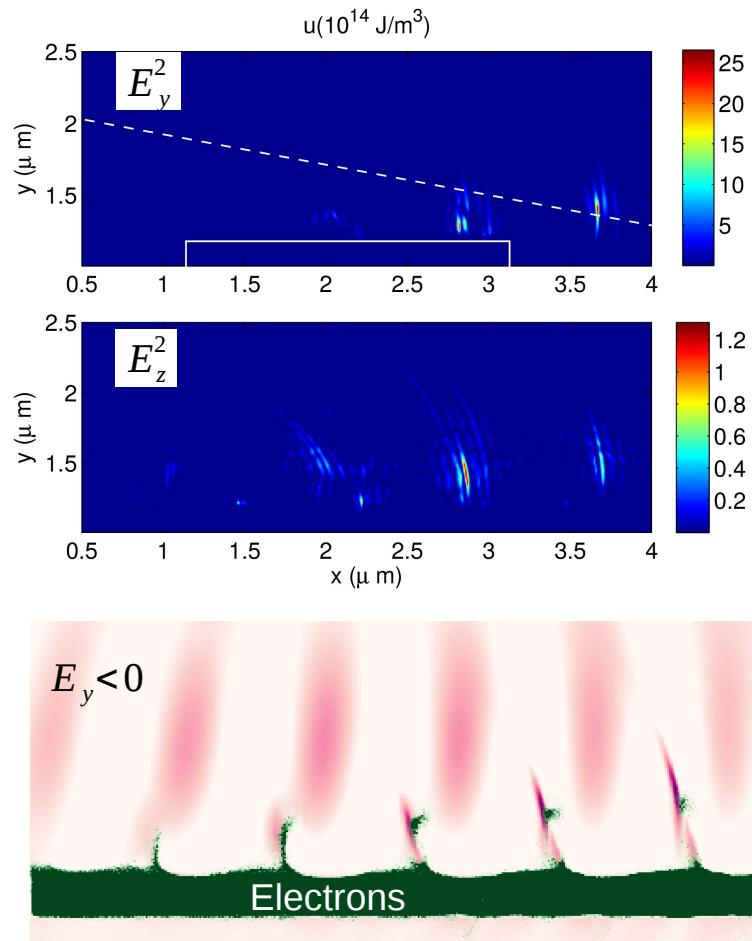
Transversal poynting vector



Coherent Synchrotron Emission

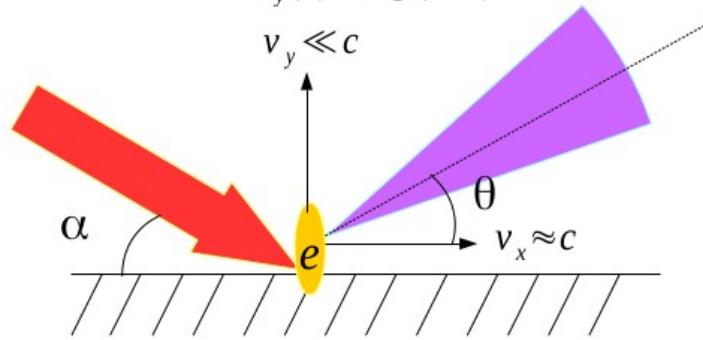


Coherent Synchrotron Emission



Schematic view:

$$\text{Acceleration: } a_y(t) \sim \exp(-t^2)$$



$$E_y(t) = \frac{-Ne}{c^2 R} \frac{a_y(t')}{(1 - v_x(t')/c)^2}$$

$$= -C a_y(t') \frac{4\gamma^4}{(1 + \alpha_1 \gamma^2 t'^{2n})^2}$$

$$x' = x - c(t - t')$$

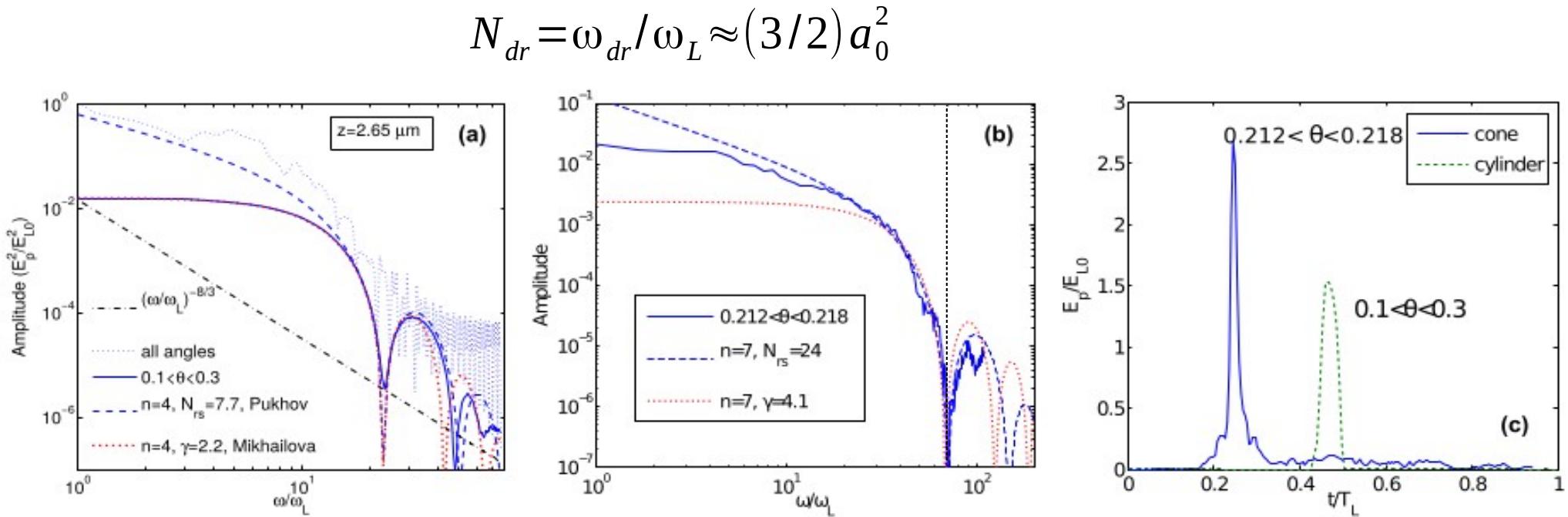
$$v_x(t') = v_0(1 - \alpha_1 t'^{2n})$$

$\rightarrow t'(t)$

J.M. Mikhailova et al., PRL **109**, 245005 (2012)

Harmonic spectrum

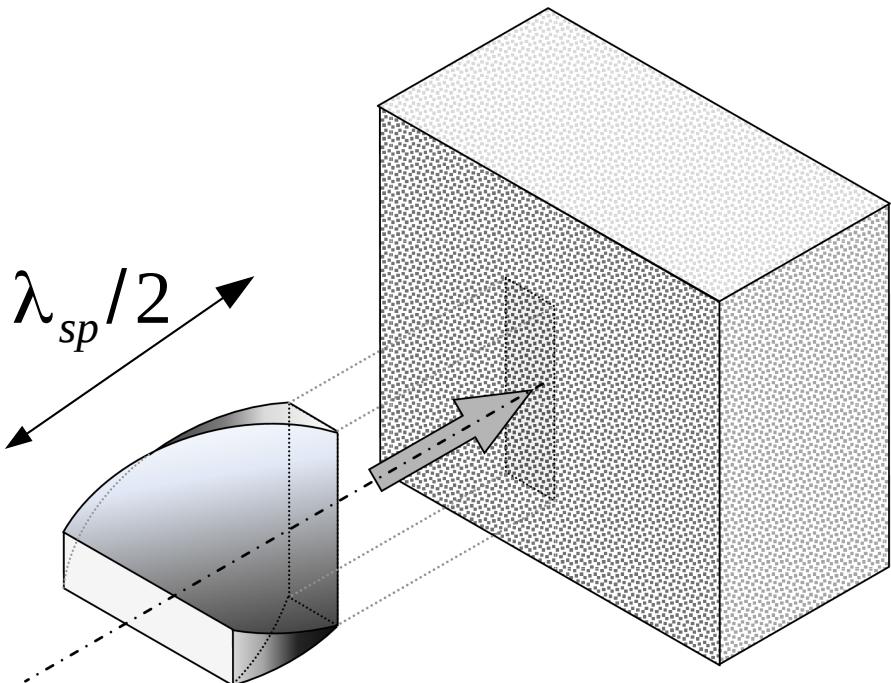
Zs. Lécz and A. Andreev, PRE **93**, 013207 (2015)



$$t_{atto} = 0.21 N_{dr}^{-1} t_L, I_{atto} = (N_{dr}/2)^2 I_{\omega_0} \quad I_{\omega_0} = ?$$

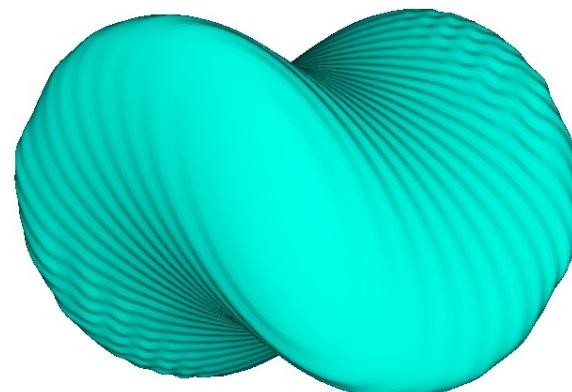
Screw-shaped laser pulse

<http://arxiv.org/abs/1604.01259>



The laser pulse is represented by the envelope function of the intensity distribution.

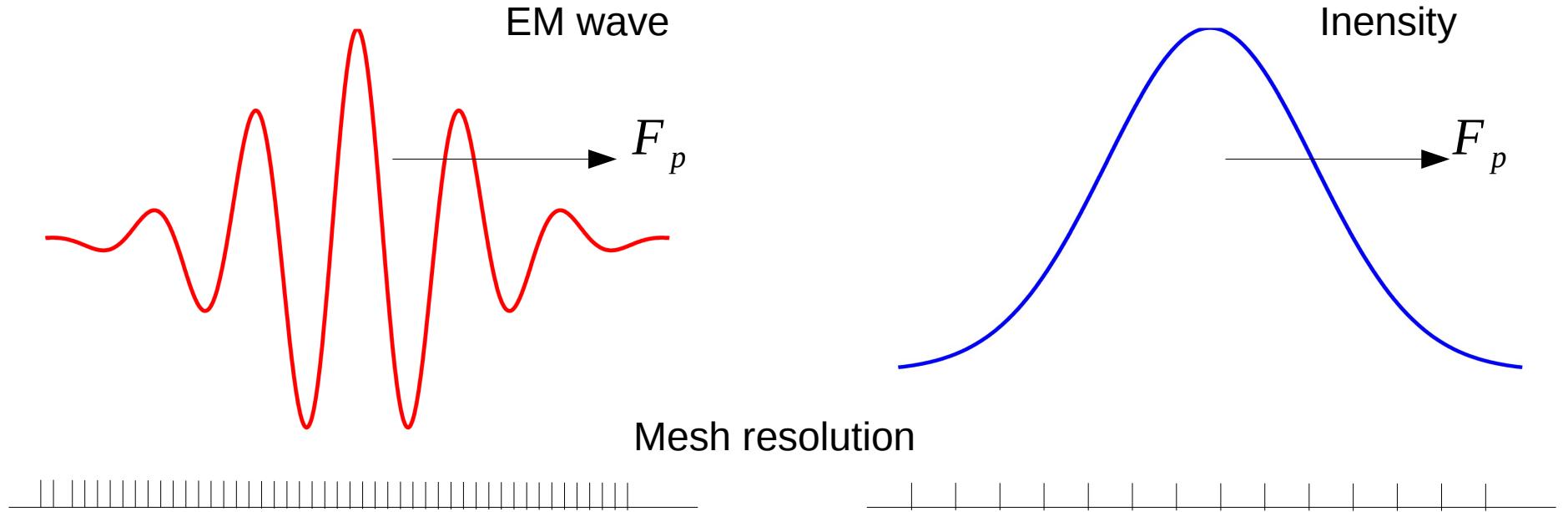
Front View:



The ponderomotive force has an azimuthal component as well!

$$F_p \sim \nabla I_L \lambda_L^2 \sim (I_L / \lambda_{sp}) \lambda_L^2$$

Envelope model



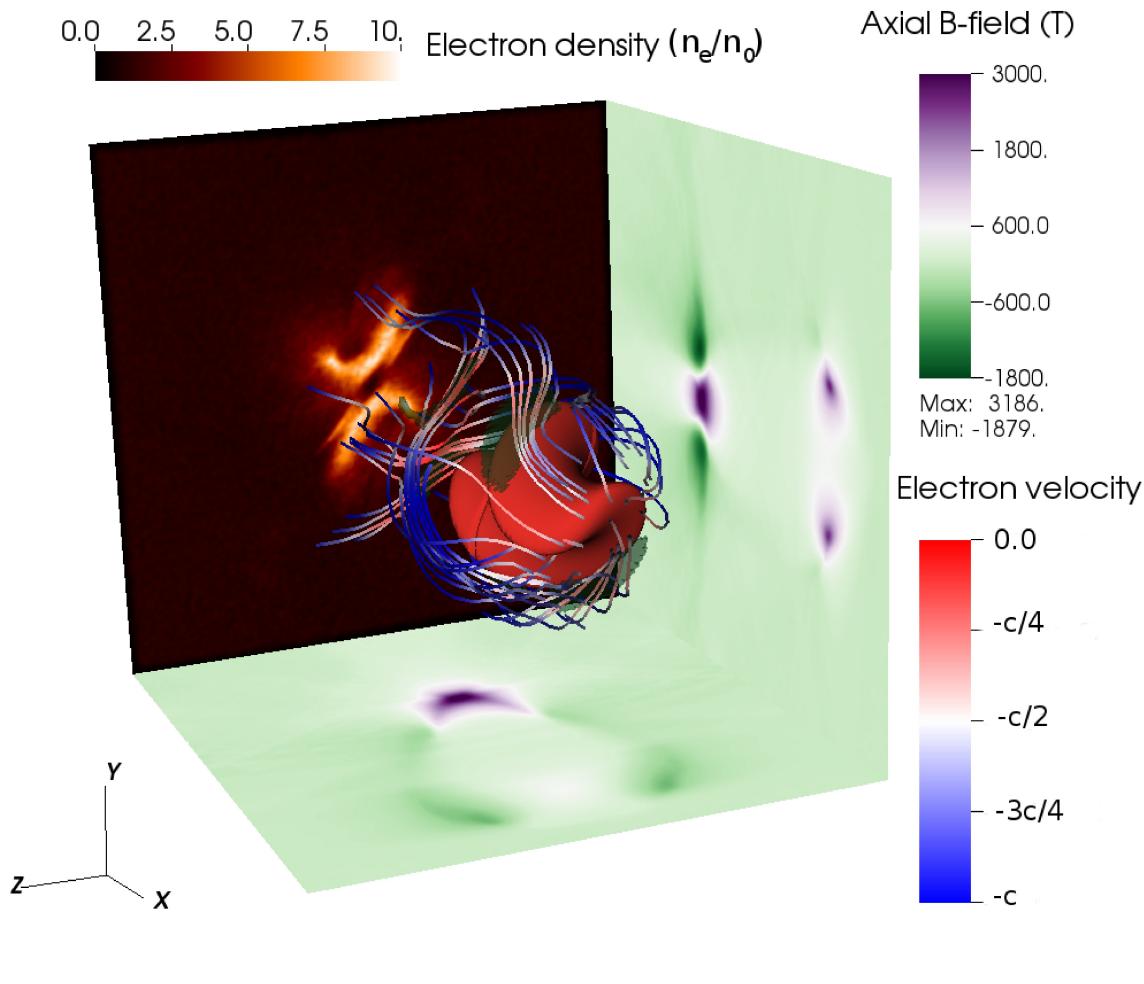
$$F_p = e \vec{v} \times \vec{B} \sim \vec{E} \times \vec{B}$$
$$\sim E \partial E / \partial x \sim \nabla E_{env}^2 \cdot [1 + \cos(2kx)]$$

If the electron plasma period is much larger than the laser period:

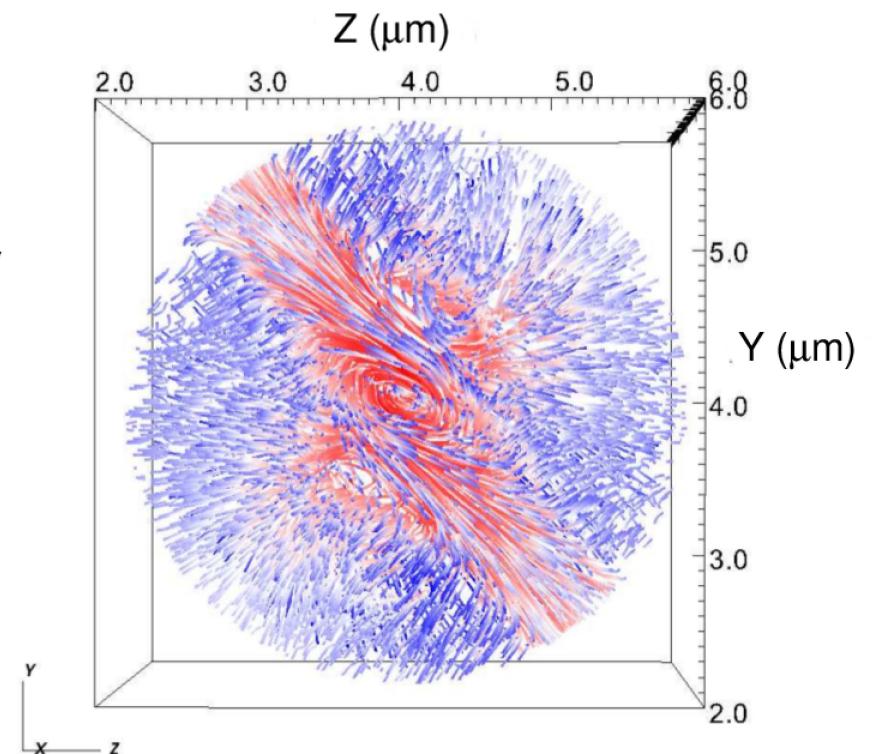
$$F_p \sim \nabla I_L$$

Electron dynamics

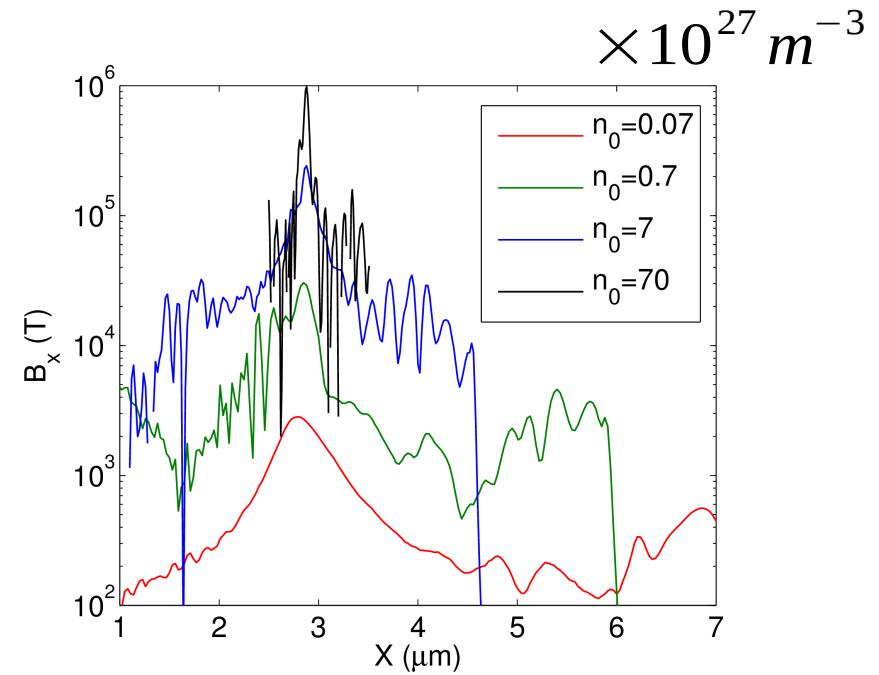
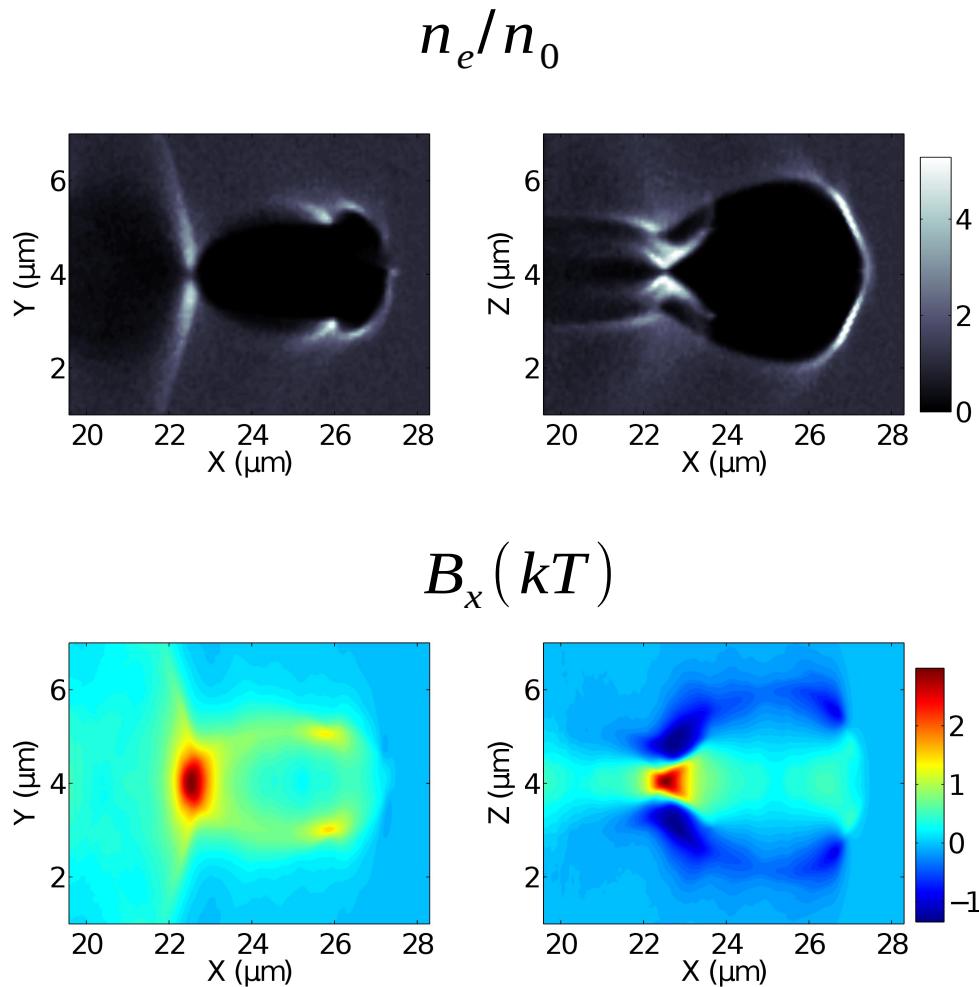
In the moving frame of the laser pulse!



In the back of the bubble.



Bubble solenoid



The plasma has to be underdense, otherwise the pulse depletion becomes significant.

Scaling of peak magnetic field

$$B \sim (\gamma n_0)^{1/2}$$

$$n_0 < 0.1 n_{cr} = \lambda_L^{-2} 1.12 \cdot 10^{14} m^{-1}$$

$$\gamma \sim I_L \lambda_L$$

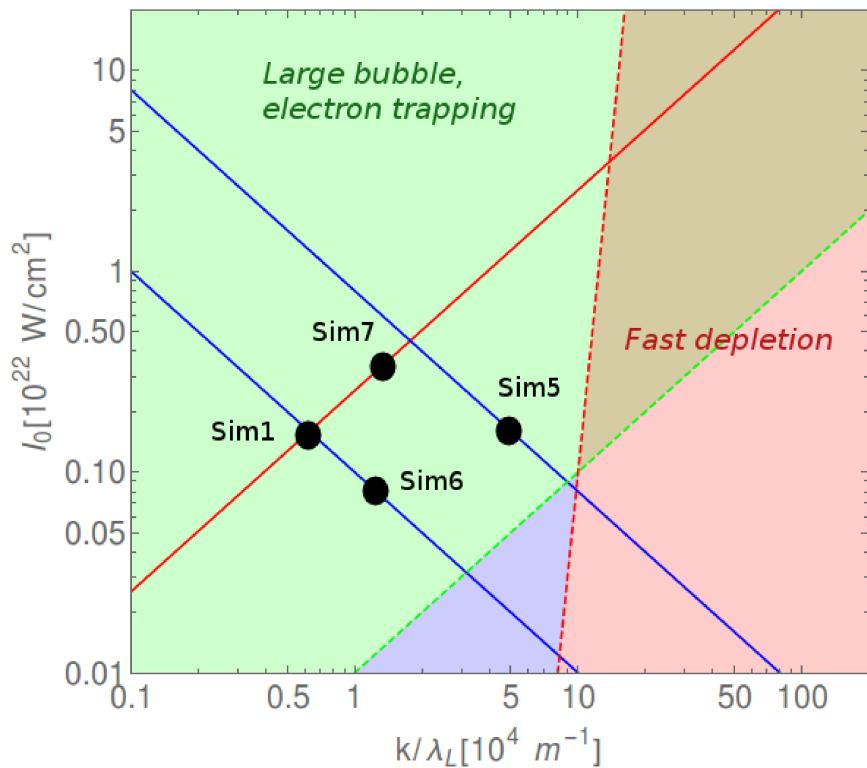
For larger B-field small wavelength and high intensity is required!!

$$B = 1 \text{ MT} \Rightarrow n_0 = 7 \cdot 10^{28} \text{ m}^{-3}, \lambda_L = 20 \text{ nm}, I_L = 8 \times 10^{23} \text{ W/cm}^2$$

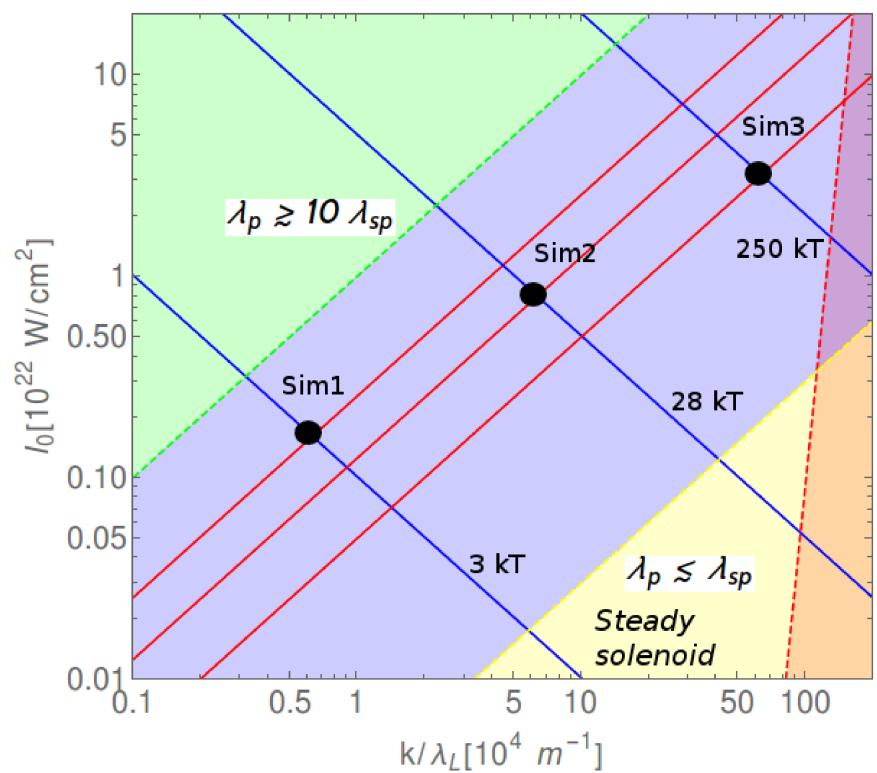
$$B = 50 \text{ kT} \Rightarrow n_0 = 7 \cdot 10^{28} \text{ m}^{-3}, \lambda_L = 800 \text{ nm}, I_L = 2 \times 10^{22} \text{ W/cm}^2$$

Parameter map

$\lambda_L = 800 \text{ nm}$



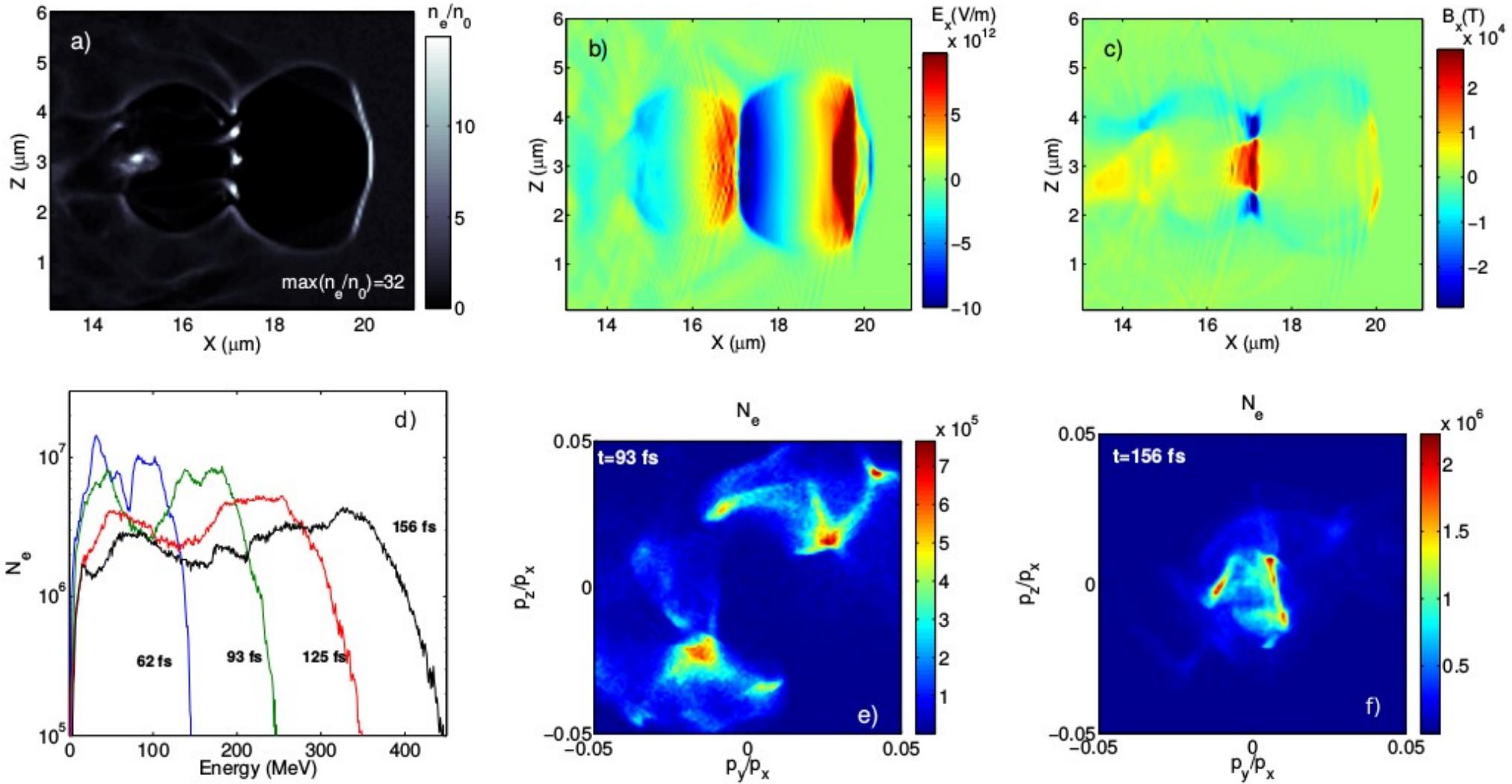
$\lambda_L = 100 \text{ nm}$



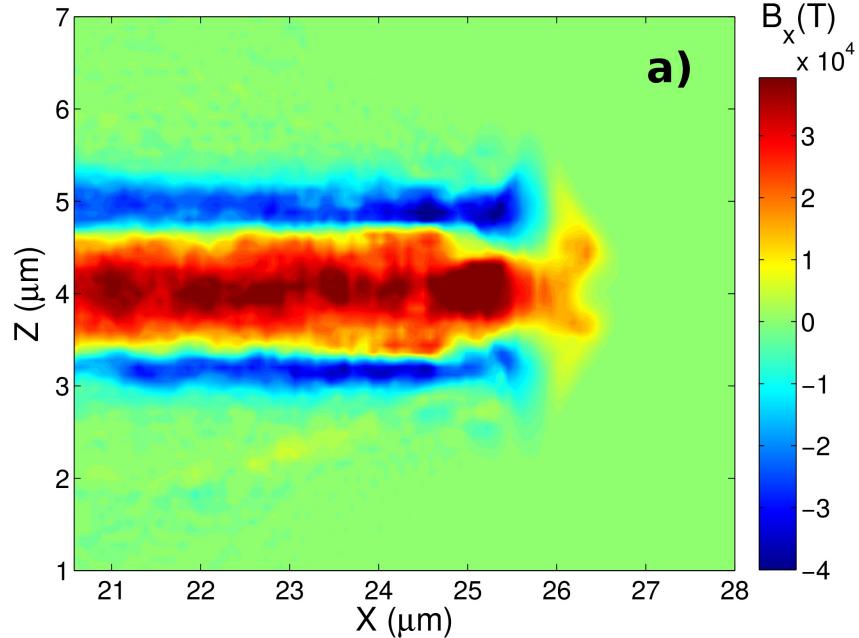
$$k = n_0/n_{cr}$$

$$\lambda_p = 2\pi c/\omega_p = \text{plasma wavelength}$$

Electron collimation: Low emittance via synchrotron cooling?



Steady solenoid



The plasma wavelength is smaller than the laser pulse length (or spiral step). In this regime bubble can not be formed, but rotational current is generated behind the pulse.

The length and lifetime of the uniform axial field depends on the depletion time and diffusion time respectively.

100 micrometers long for 100 fs

Future plans

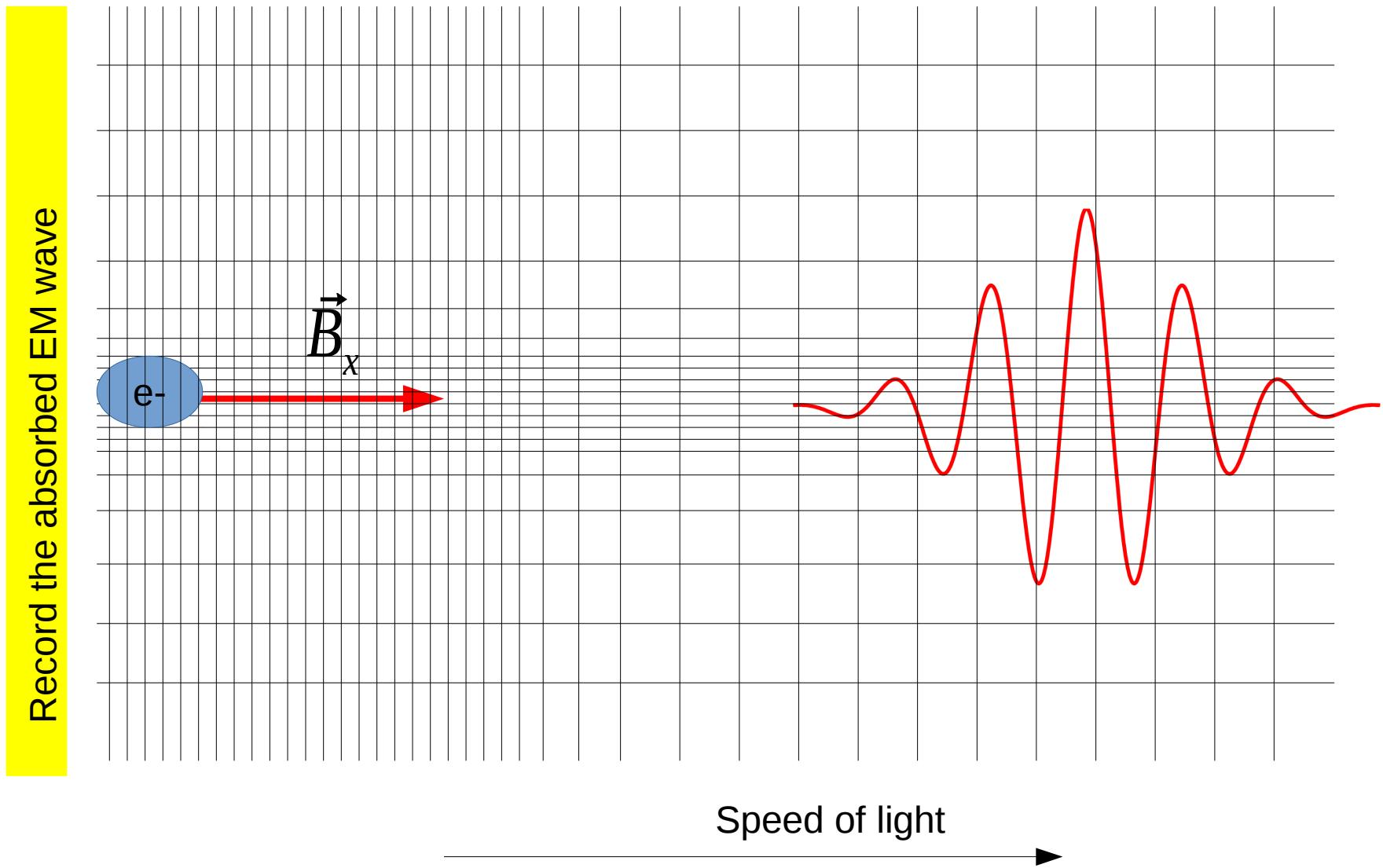
Project 1

- Electron cooling via synchrotron emission
- Near the laser axis higher grid resolution is needed
- Improved beam emittance? New short wavelength source ?

Project 2

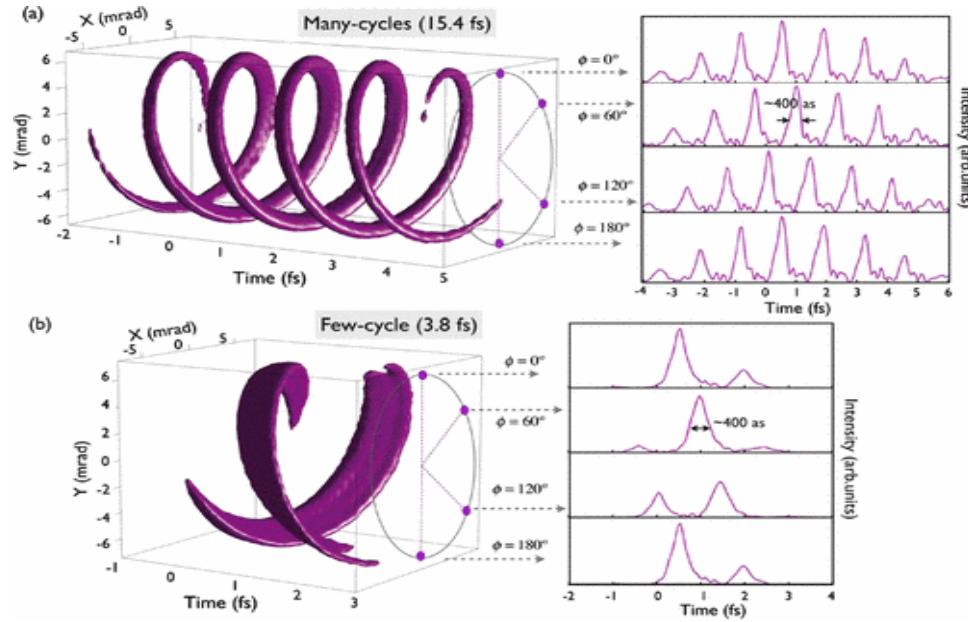
- Generalize the driver beam: does it work with e-beam as well?
-
-

Multi-scale problem



Thank you for your attention!

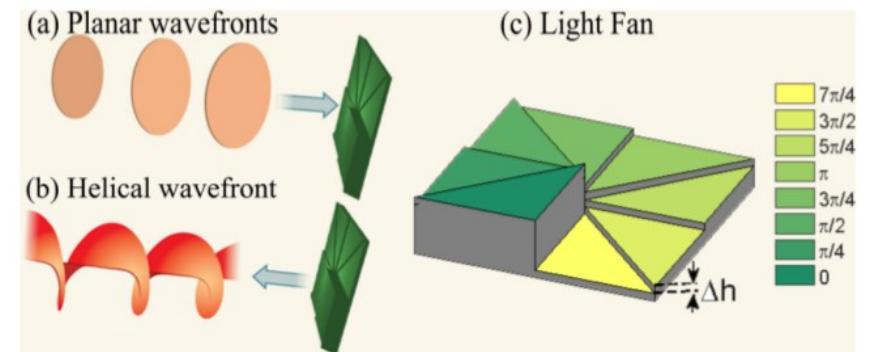
Twisted pulses (using plasmas)



OAM conversion of Laguerre-Gaussian pulses
Attosecond UV vortex

In gas target:

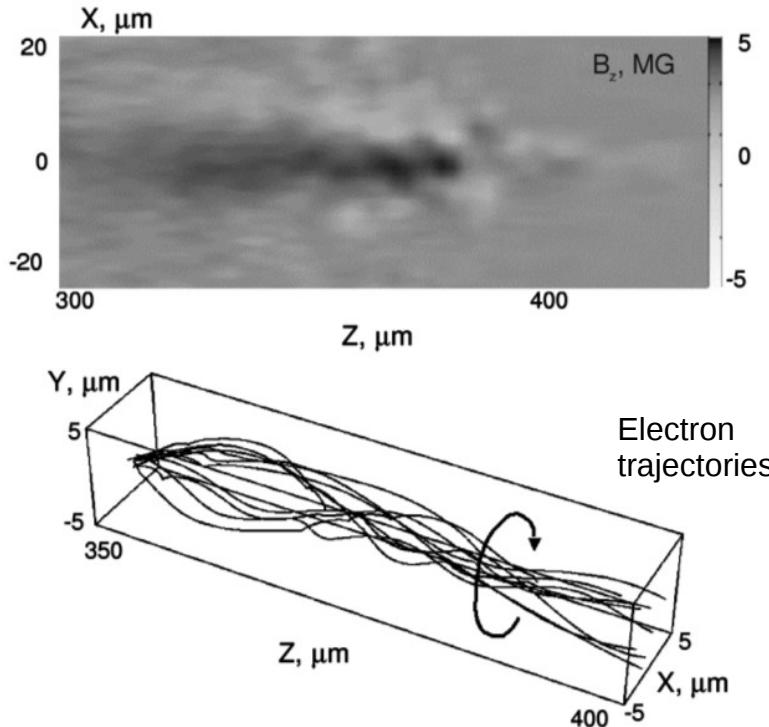
Carlos Hernandez-Garcia et al.,
Physical Review Letters **111**, 083602
(2013)



Yin Shi et al., Physical Review Letters
112, 235001 (2014)

The wavefront of the incoming pulse is distorted by the tailored spiral-shaped surface.

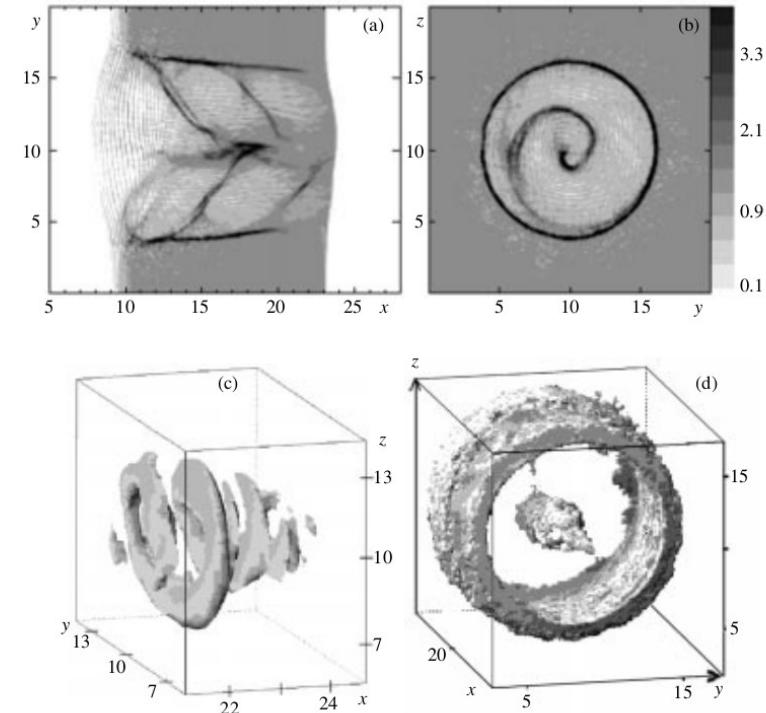
Collimated electron and ion beams



Z. Najmudin et al., Phys Rev Lett
87, 215004 (2001)

Axial magneic field:

N. Naseri et al., PHYSICS OF PLASMAS 17,
083109 (2010)



S. V. Bulanov et al., JETP Letters, Vol.
71, No. 10, 2000, pp. 407–411

Inertial Confinement Fusion:

T. AKAYUKI , A. & K EISHIRO , N. (1987).
Laser Part. Beams 5, 481–486