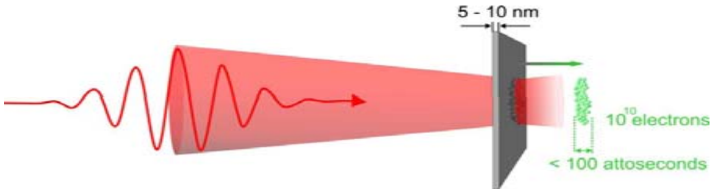
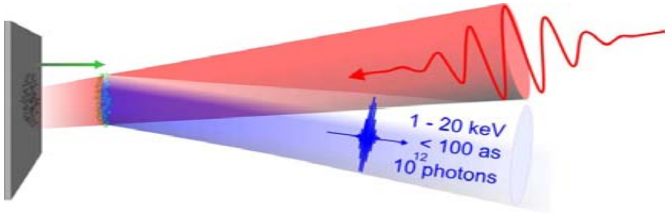
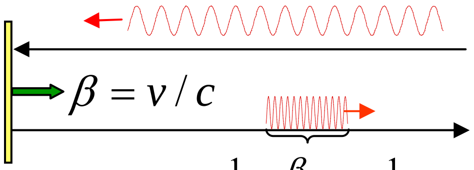
Laser-driven relativistic electron layers for coherent Thomson scattering

J. Meyer-ter-Vehn, Hui-Chun Wu, Xueqing Yan, MPQ Garching





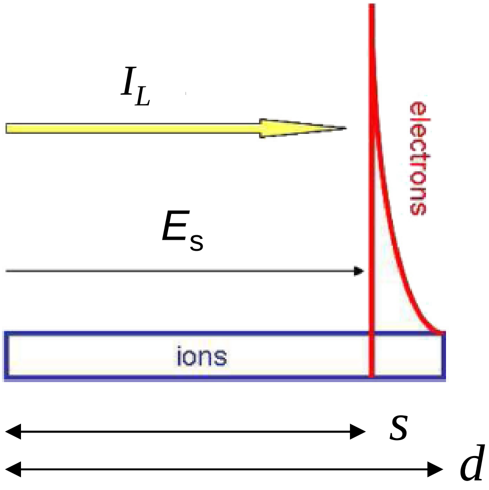


$$\sim \frac{1-\beta}{1+\beta} \approx \frac{1}{4\gamma^2}$$

A. Einstein, Annalen der Physik 17, 891 (1905)

Challenge: Ultrathin foils - high contrast laser pulses

Charge separation



$$\varepsilon_0 E_s^2 / 2 \approx I_L / c$$

$$eE_s = m\omega_p^2 \cdot s$$

$$10 - 100 \text{ MV/μm}$$

Ion acceleration regime *(s ~ d)*

For laser fields

$$a_0 \approx \varepsilon_0 = (n_e / n_{crit}) k_L d$$

the electrostatic field just
balances the light pressure
and the whole foil is accelerated.

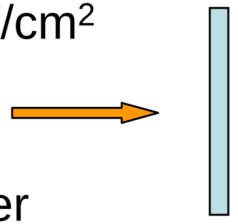
This requires ultra-thin foils
in the order of 10 - 100 nm thick.

Also circular polarized light
is needed to keep electrons cold!

PRL 103, 245003 (2009) PHYSICAL REVIEW LETTERS week ending 11 DECEMBER 2009

Radiation-Pressure Acceleration of Ion Beams Driven by Circularly Polarized Laser Pulses

A. Henig,[1,2,*] S. Steinke,[3] M. Schnürer,[3] T. Sokollik,[3] R. Hörlein,[1,2] D. Kiefer,[1,2] D. Jung,[1,2] J. Schreiber,[1,2,4] B. M. Hegelich,[2,5] X. Q. Yan,[1,6,†] J. Meyer-ter-Vehn,[1] T. Tajima,[2,7] P. V. Nickles,[3] W. Sandner,[3] and D. Habs[1,2]



5.3 nm
DLC foil

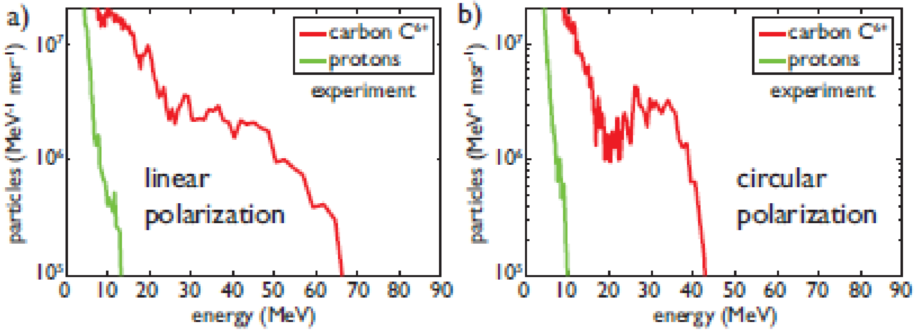
$5\text{x}10^{19}$ W/cm^2

MBI laser

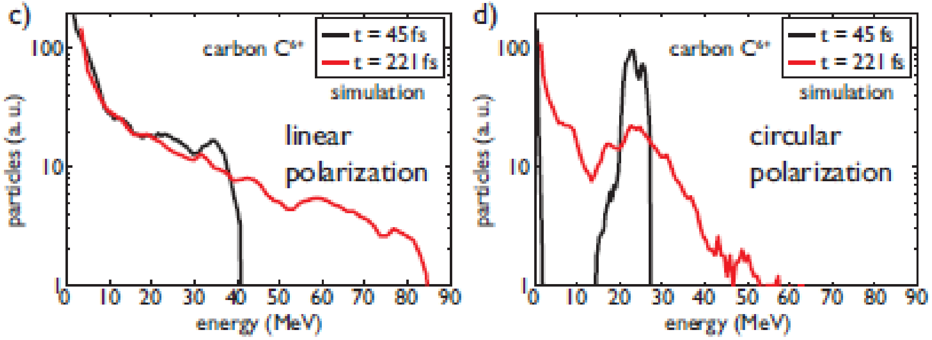
experiment

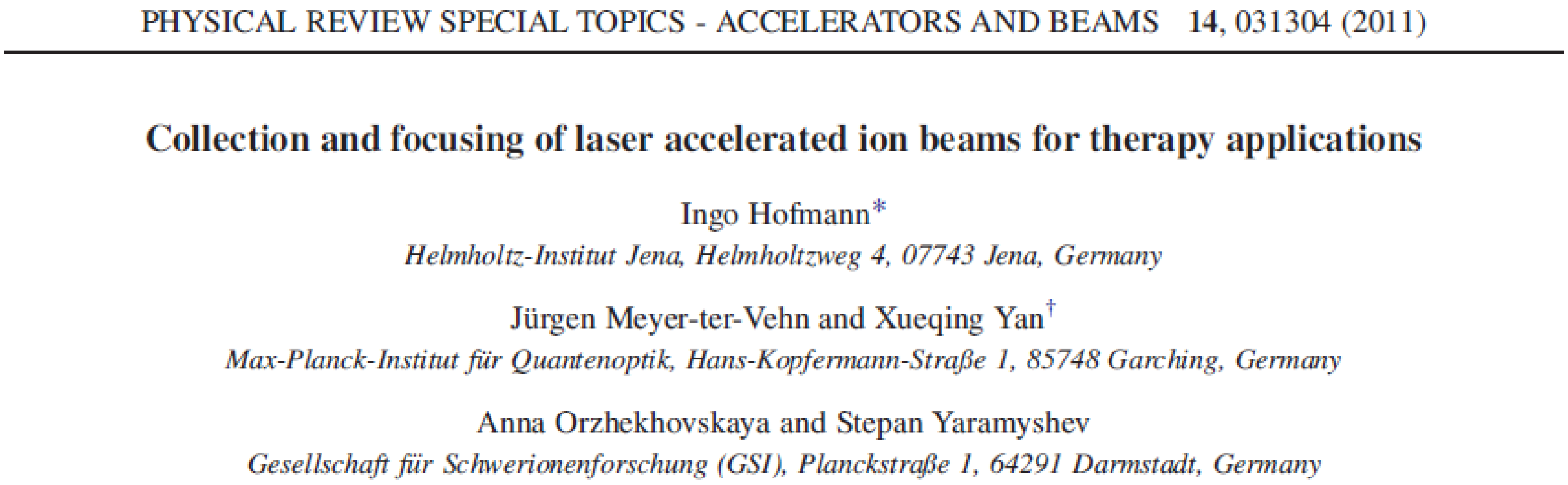
linear

circular



simulation





PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 14, 031304 (2011)

Collection and focusing of laser accelerated ion beams for therapy applications

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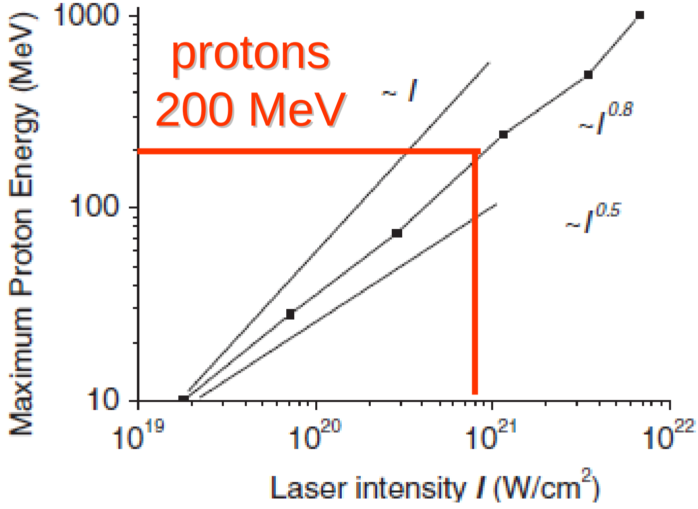
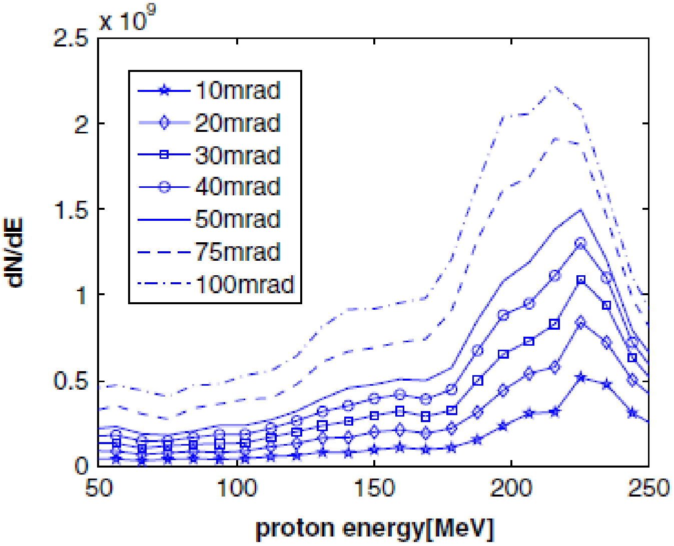


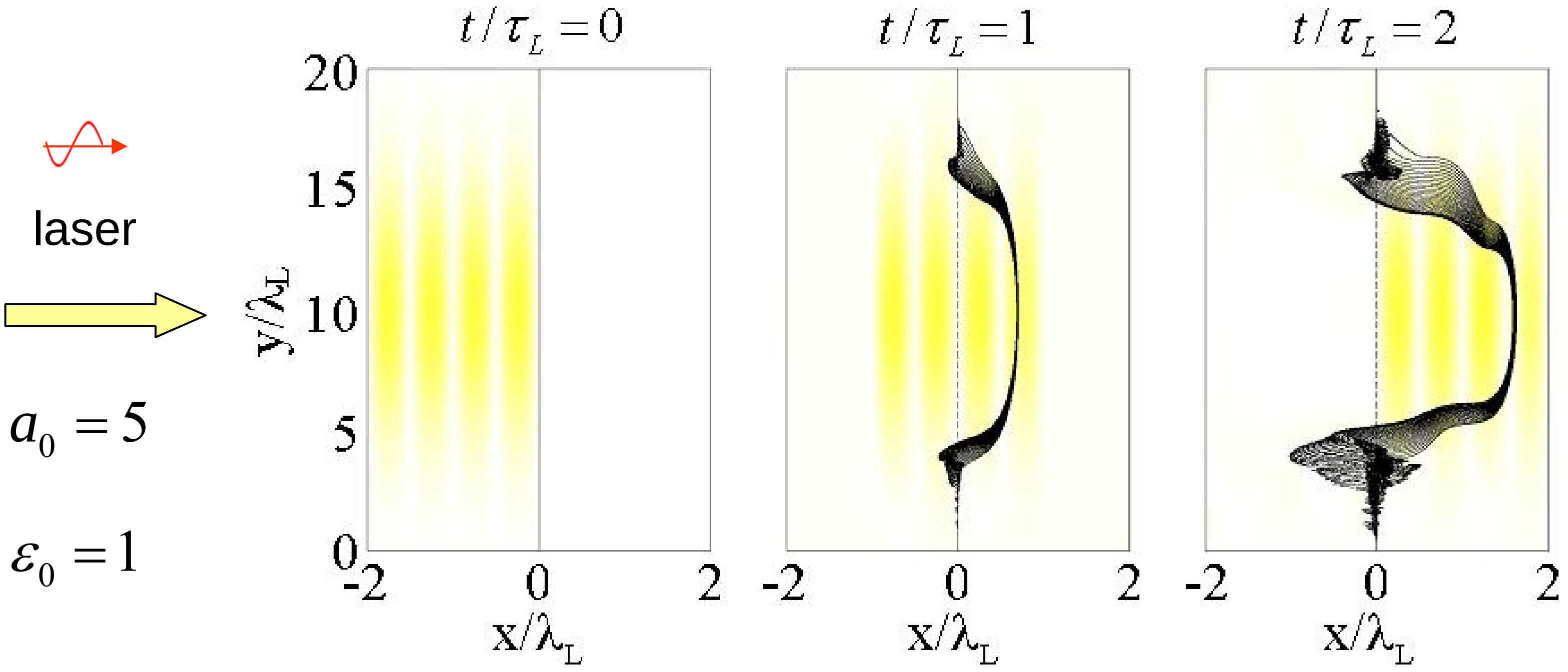


620 J, 62 fs, 10 PW laser pulse
400 nm foil

Even thinner foils:

Electron blow-out regime ($a_0 > \varepsilon_0$)

J. Meyer-ter-Vehn and Huichun Wu, Eur. Phys. J. D55, 455 (2009)



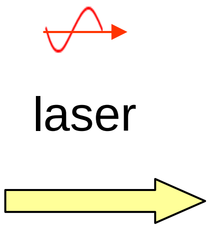
laser

$a_0 = 5$

$\varepsilon_0 = 1$

$\gamma_{\max} \approx 19$

Electron density and γ evolution

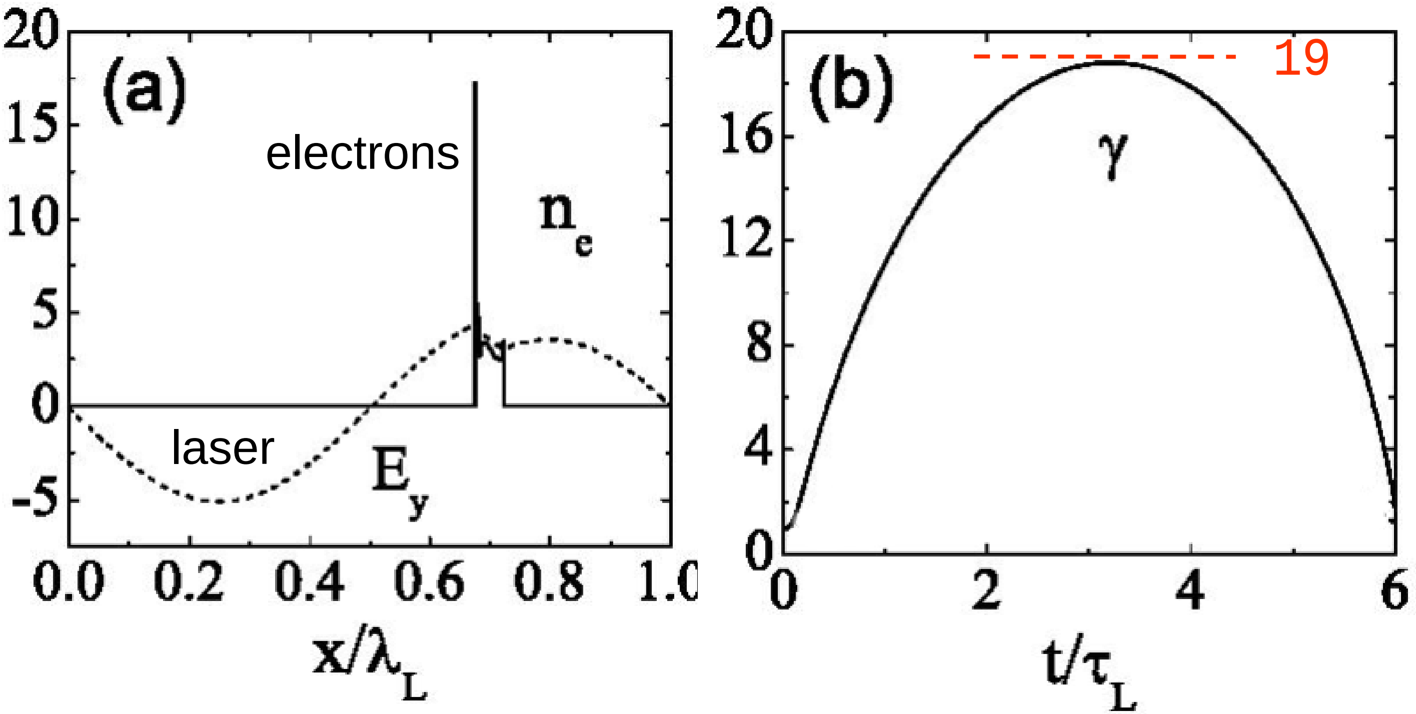


$a_0 = 5$

$\varepsilon_0 = 1$

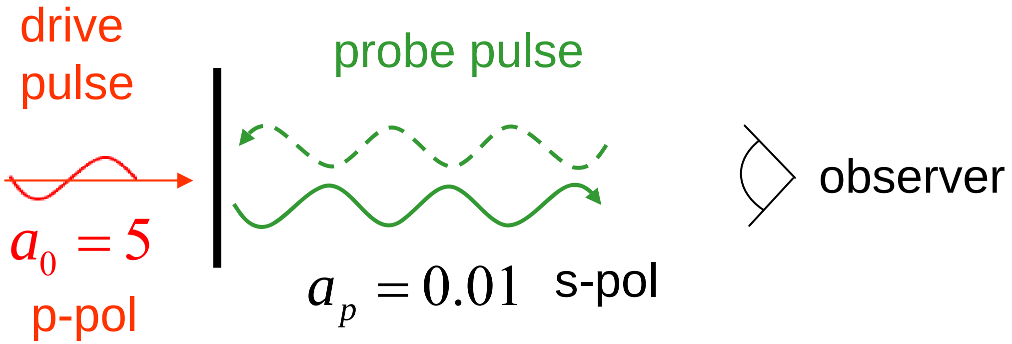
electron layer
after1 cycle of interaction,
wave front depleted due
to electron acceleration.

γ evolution
of electrons
at front peak



Expected backscattered probe light upshift $4\gamma_{\max}^2 \approx 4\times 19^2 \approx 1444$

Back-scattered spectrum (1D-PIC)



drive pulse

probe pulse

observer

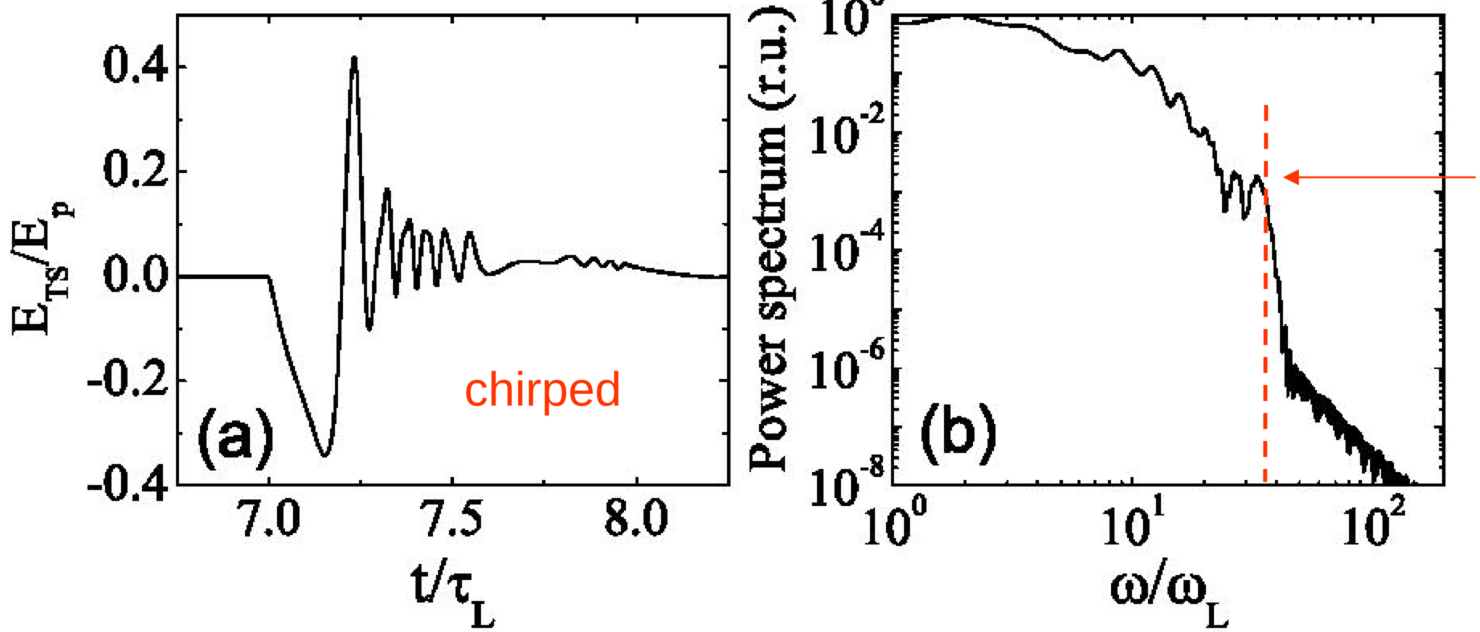
$a_0 = 5$

p-pol

$a_p = 0.01$ s-pol

backscattered signal

spectrum



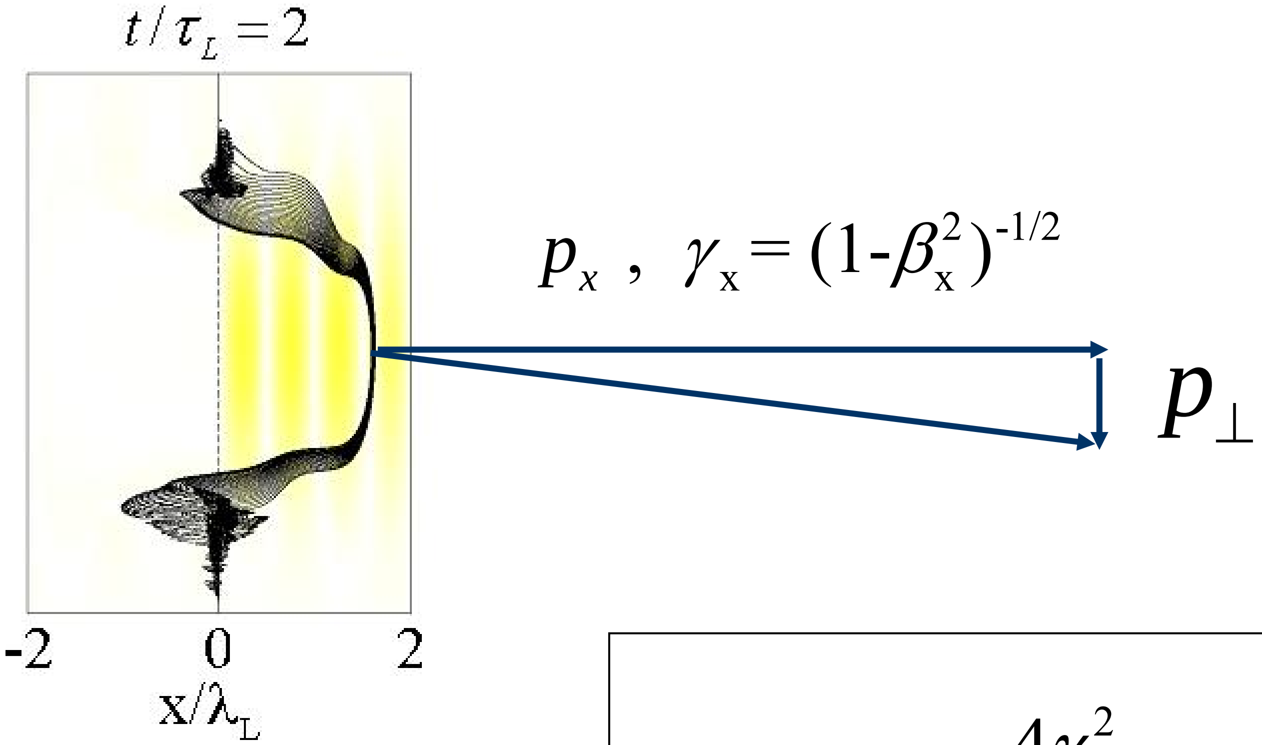
$$\frac{\omega}{\omega_0} = 4\gamma_x^2$$

$$\simeq 36$$

$$\gamma_x = 3$$

Great disappointment ! Spectral cutoff at $36\ \omega_0$, not at $1444\ \omega_0$!

For coherent Thomson scattering,
transverse momentum $p_\perp$ degrades Doppler factor



$p_x\ ,\ \gamma_x = (1-\beta_x^2)^{-1/2}$

$p_\perp$

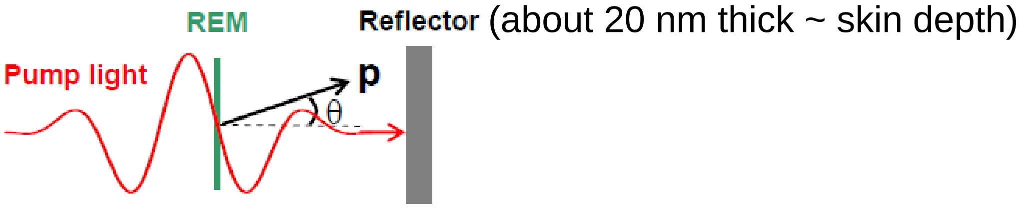
$$4\gamma_x^2 = \frac{4\gamma^2}{1+(p_\perp/mc)^2} \approx 2\gamma$$

PRL **104,** 234801 (2010) PHYSICAL REVIEW LETTERS week ending 11 JUNE 2010

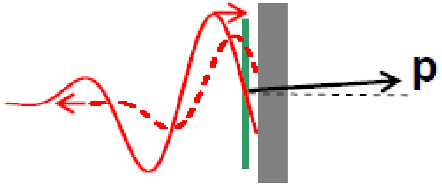
Uniform Laser-Driven Relativistic Electron Layer for Coherent Thomson Scattering

H.-C. Wu (武慧春),[1,*] J. Meyer-ter-Vehn,[2] J. Fernández,[1] and B. M. Hegelich[1,3]

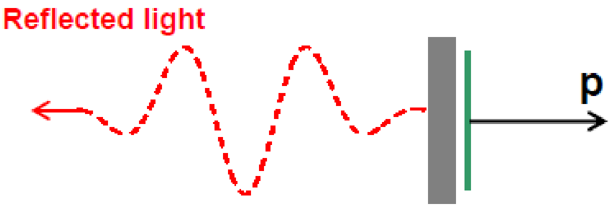
New idea how to suppress transverse electron momentum $p_\perp$:
Use additional reflector reflecting pump light,
but let relativistic electrons (REM) pass unperturbed!



Reflected light turns $p_\perp \to 0$,
while changing p_x only marginally!

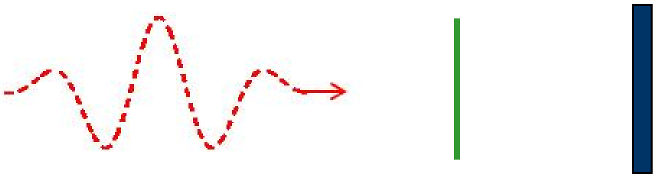


Relativistic electrons emerge
from reflector with $p_\perp = 0$.



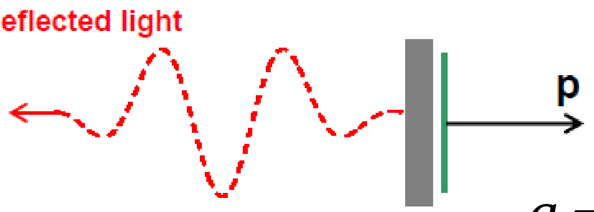
Simple argument to understand $p_\perp \to 0$

Conservation of canonical momentum $p_\perp - a = \text{const}$



$p_\perp = 0$

$a = 0$



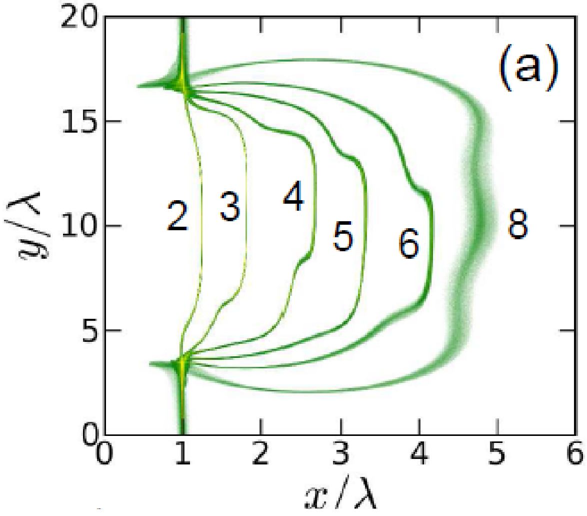
$a = 0$

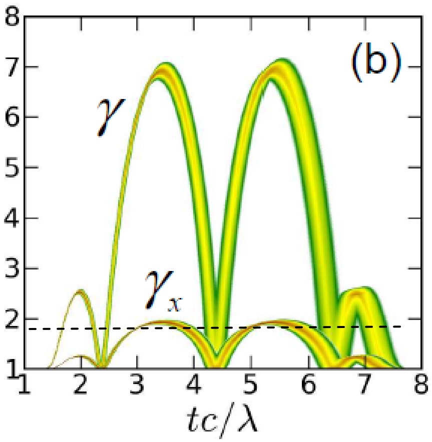
$p_\perp = 0$

2D-PIC simulations
H.C. Wu (2010)

$$a_0 = 3.5, \quad n_e / n_{crit} = 1, \quad d / \lambda = 0.001$$

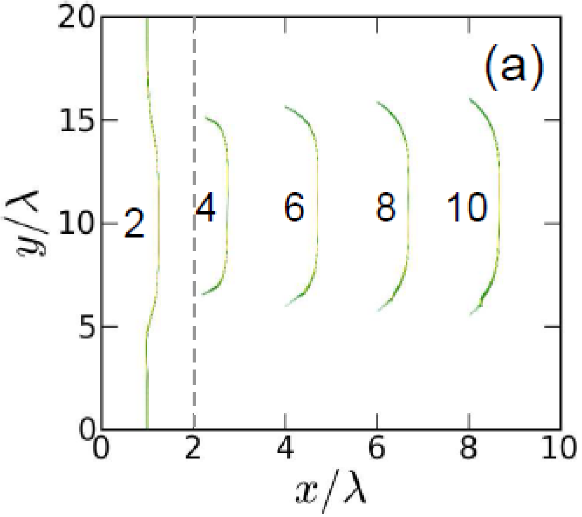
without reflector

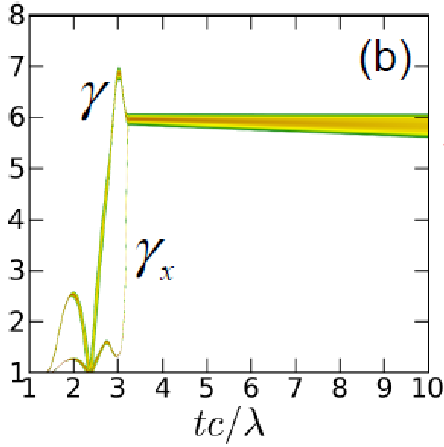




$\gamma_{x,\max} \approx 1.8$

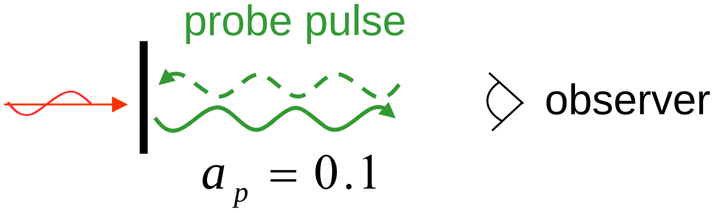
with reflector



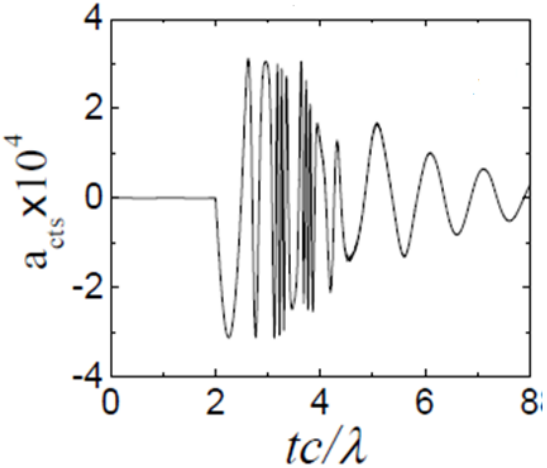


$\gamma \approx 5.85$

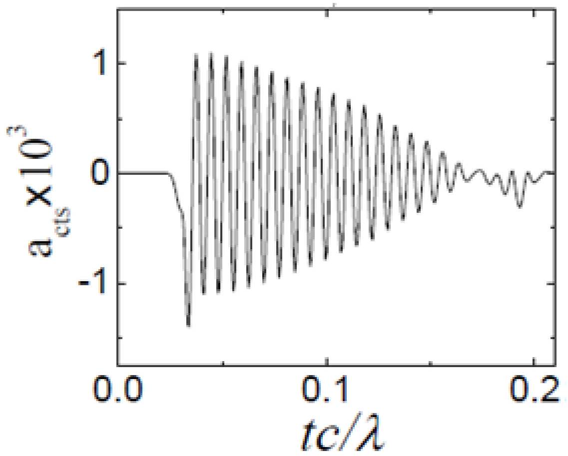
Signal and spectrum from electron mirror



without reflector

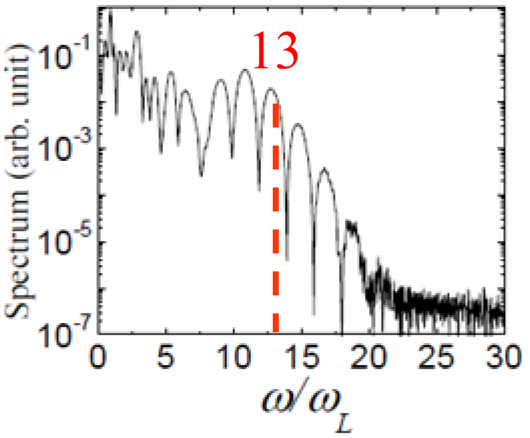


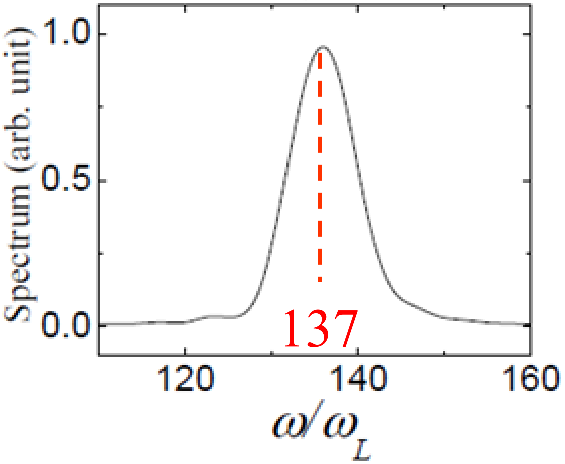
with reflector



$\gamma_{x,\max} \approx 1.8$

$4\gamma_{x,\max}^2 \approx 13$



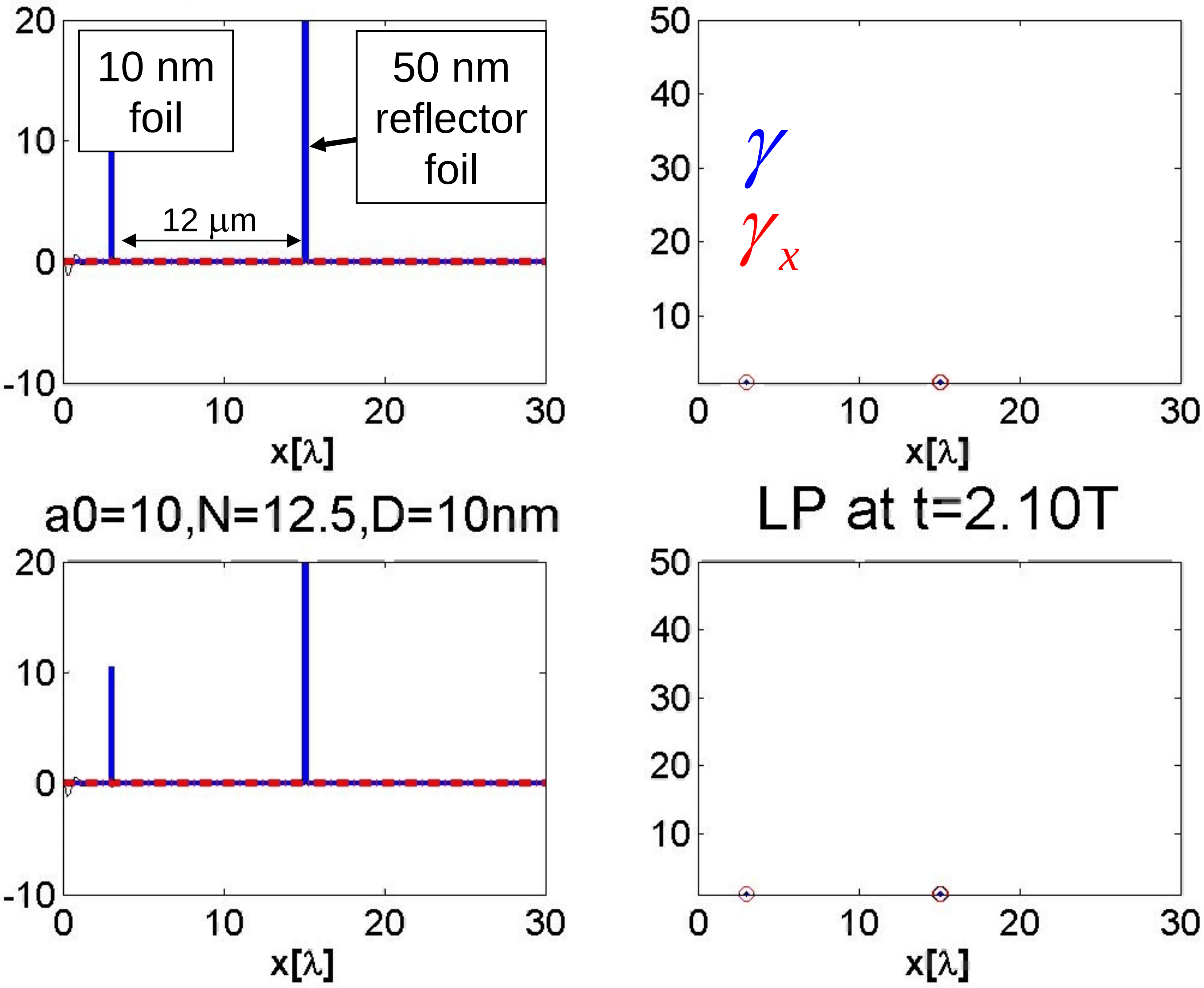


$\gamma \approx 5.85$

$4\gamma^2 \approx 137$

circ. pol.

50 fs,
10^{20} W/cm^2
laser pulse

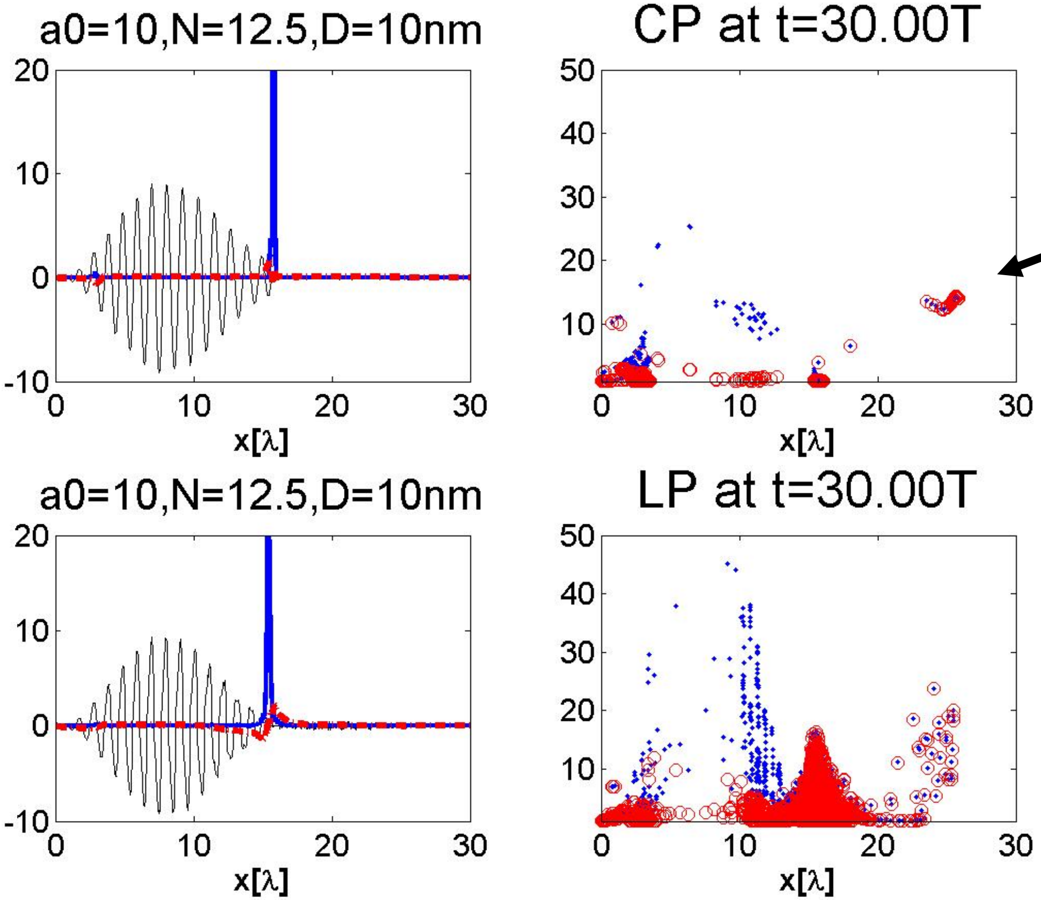


linear pol.

Case for experiments now

— γ — γ_x

Last picture of movie in previous viewgraph



Electron sheet emerging from reflector foil

with $\gamma_x = \gamma \approx 14$

Reflectivity of relativistic mirror

H.C. Wu, J. Meyer-ter-Vehn, et al. PRL104, 234801 (2010)

Electron density:

$$n_e(x) = n_0 \; S(x/d)$$

Coherently backscattered amplitude:

$$a_{\mathrm{refl}} / a_{\mathrm{inc}} = \gamma \frac{n_0 k_{\mathrm{L}} d}{n_{\mathrm{crit}}} F(\xi)$$

Form factor:

$$F(\xi) = \int_{-\infty}^{\infty} S(\chi) \; \cos(\chi\xi) \, d\chi$$

in rest frame of mirror $\chi = x'/d'$ $\xi = 2k'_L d'$

in lab frame $\xi = 2\gamma^2(1+\beta) \, k_L d \;\approx\; 2\pi d/\lambda_{\mathrm{refl}}$

for Gaussian profile :

$$S(\chi) = \exp(-\pi\chi^2)$$

$$F(\xi) = \exp\left(-\frac{\xi^2}{4\pi}\right) = \exp\left(-\left(\frac{d}{2\lambda_{\mathrm{refl}}}\right)^2\right)$$

Reflected amplitude decays exponentially for

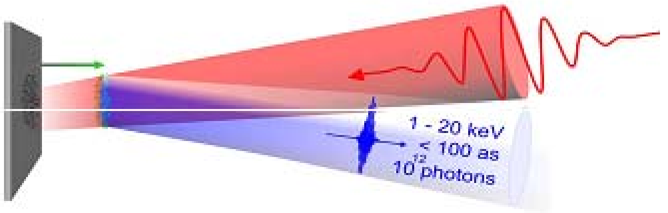
$$\lambda_{\mathrm{refl}} < d$$

Non-linear coherent Thomson scattering

H.C. Wu, J. Meyer-ter-Vehn, et al. PRSTAB (submitted 2011)

Doppler factor :

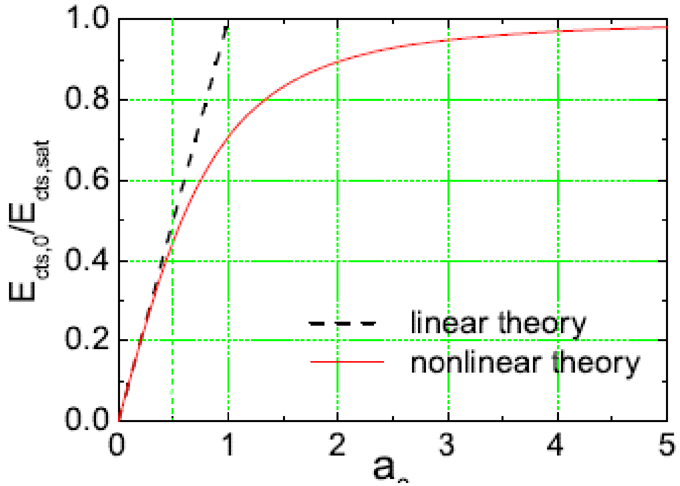
$$D \; = \; 4\gamma_x^2 \; / \; (1+a_{probe}^2)$$



$$a_{\mathrm{probe}} > 1$$

Reflected amplitude :

$$\frac{E_{\mathrm{refl}}}{E_{\mathrm{inc}}} = \frac{\gamma n_0 k_L d}{n_{crit}} \cdot \frac{F(2\pi d/\lambda_{\mathrm{refl}})}{(1+a_{probe}^2)}$$



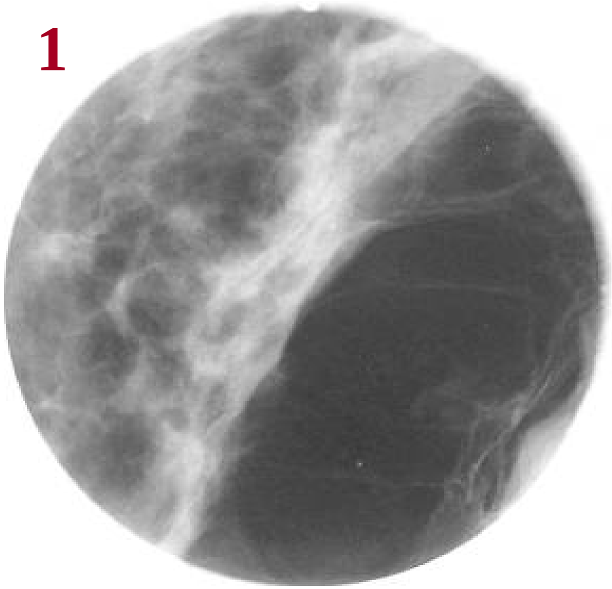
Ultimate goal: medical application

- **medical** applications require photons above 20 keV
- **phase-contrast imaging** :

  phase shifts much stronger than absorption,

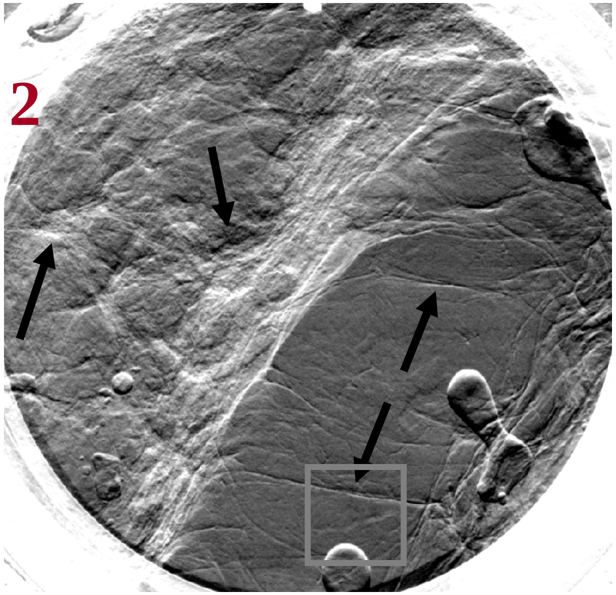
  breast cancer tissue, photographs by ESRF

1



X-ray absorption

2



same with phase-contrast

Conclusions

Relativistic electron mirrors can be used to compress probe pulses and to upshift frequency by factors $4\gamma^2$.

Coherent backscattering requires dense electon sheets.
They can be produced by blowing out all electrons
from ultrathin foils with a strong drive laser pulse.

Transverse electron momentum degrading the Doppler-shift factor
can be removed by reflecting the drive laser pulse by a reflector foil
That lets the relativistic electron layer pass almost unperturbed.