Giant half-cycle attosecond pulses from ultra-thin foils

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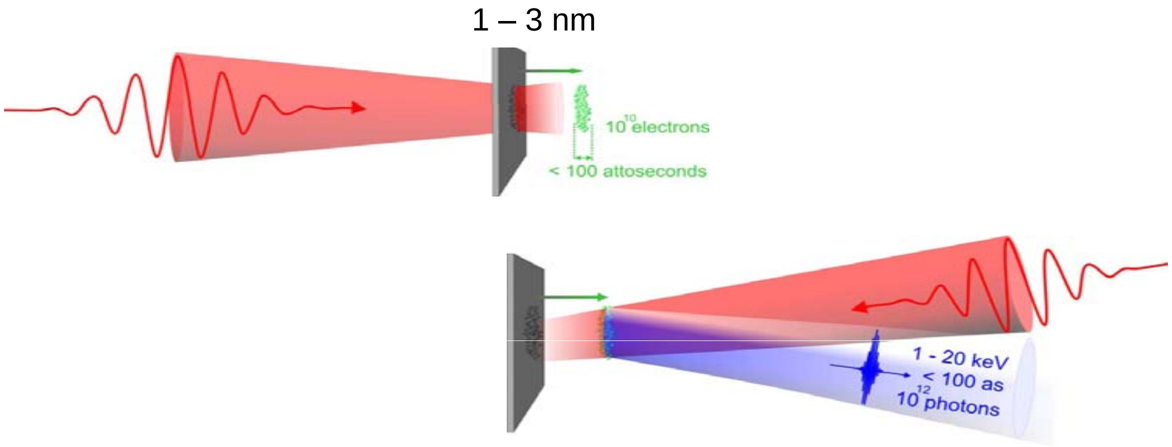
Hui-Chun Wu

publications
:

Uniform laser-driven relativistic electron layer for coherent Thomson backscattering
H.C. Wu, J. MtV et al., PRL 104, 234801 (2010)

Giant half-cycle attosecond pulses
H.C. Wu and J. MtV, Nature Photonics 6, 304 (2012)

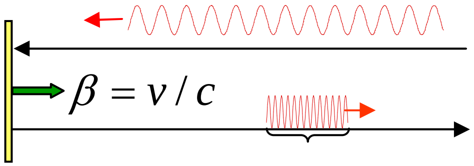
Relativistic Electron Mirror: Thomson Backscattering



$\gamma = 50,\ 4\gamma^2 = 10000$

$1\ \text{eV} \rightarrow\ 10\ \text{keV photon}$

$10\ \text{fs} \rightarrow 1\ \text{as pulse}$

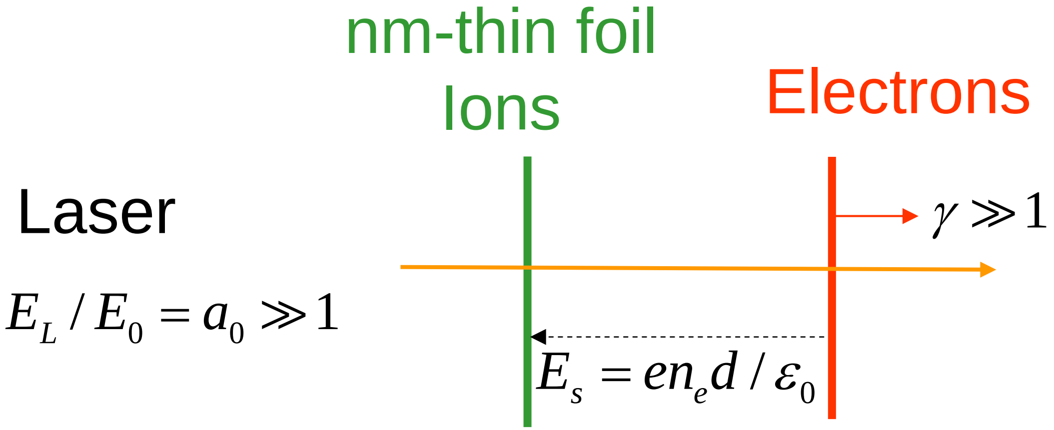


$$\sim \frac{1-\beta}{1+\beta} \approx \frac{1}{4\gamma^2}$$

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

Electron blow-out from ultrathin foils

(overdense, but transparent)



nm-thin foil

Ions

Electrons

Laser

$$E_L / E_0 = a_0 \gg 1$$

$$\gamma \gg 1$$

$$E_s = e n_e d / \varepsilon_0$$

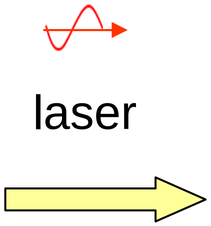
For blow-out: $E_L \gg E_s$

1 nm Diamond-Like-Carbon (DLC): $E_s \approx 18\ \mathrm{TV/m} \quad (a_s \approx 5)$

Monoatomic Graphene: $E_s \approx 0.75\ \mathrm{TV/m} \quad (a_s \approx 0.2)$

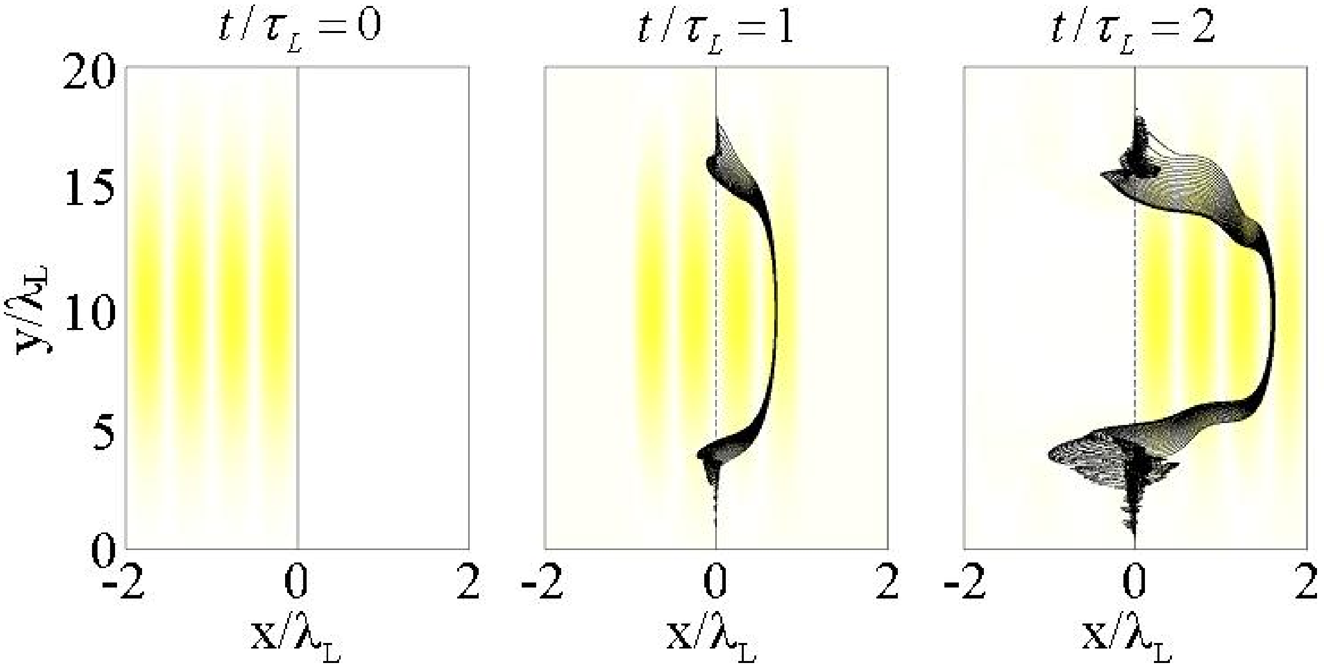
Generation of Relativistic Electron Sheet (2D-PIC)

J. Meyer-ter-Vehn and Huichun Wu, Eur. Phys. J. D55, 455 (2009)
see also Kulagin et al. PRL 99, 124801 (2007).



laser

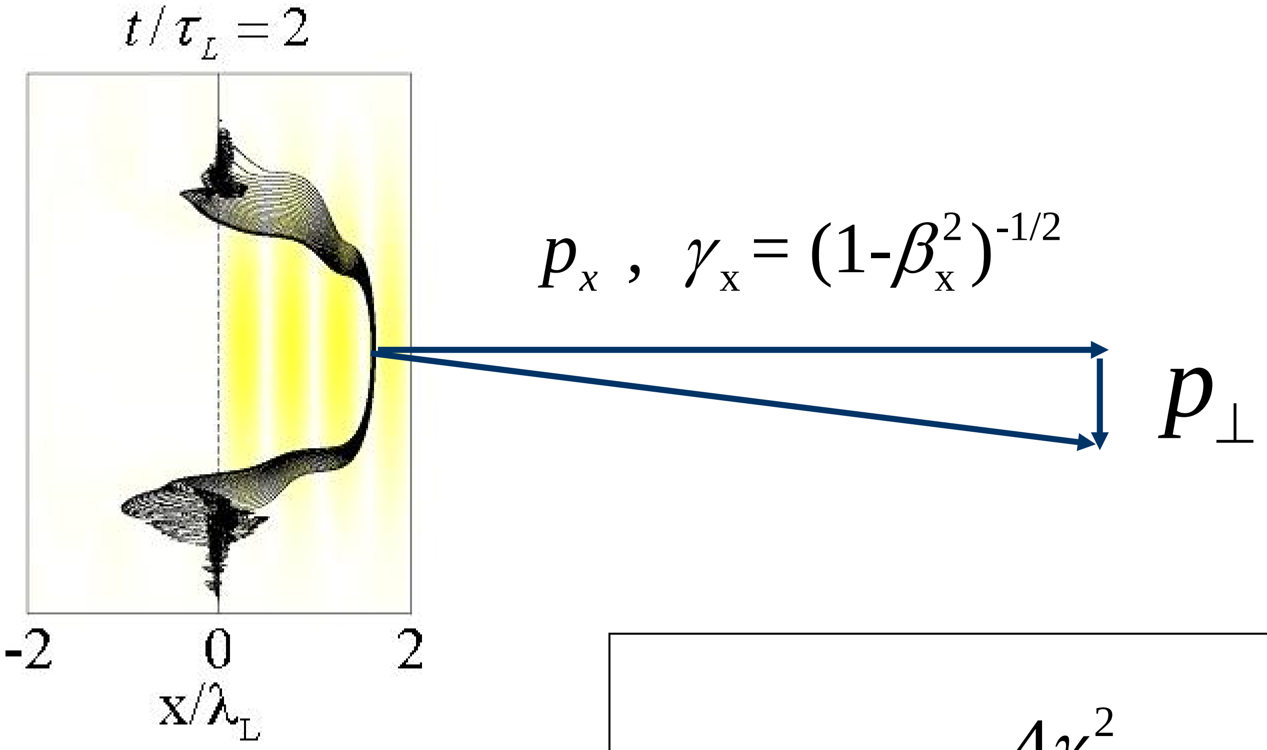
$a_0 = 5$



$\gamma_{\max} \approx 19$

$4\gamma_{\max}^2 \approx 1444$

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

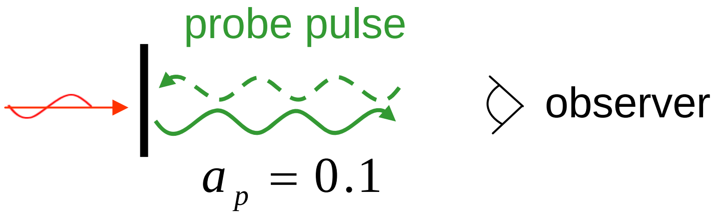


p_x , $\gamma_x = (1-\beta_x^2)^{-1/2}$

$p_\perp$

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

Signal and spectrum from electron mirror

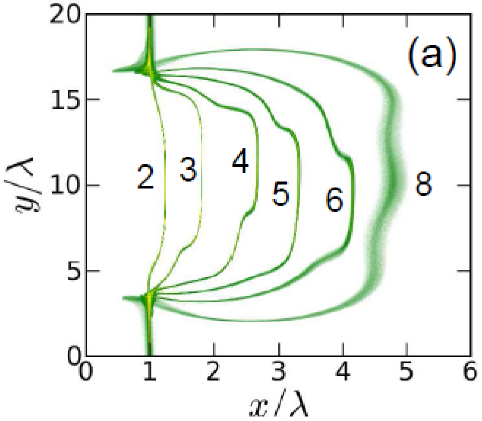


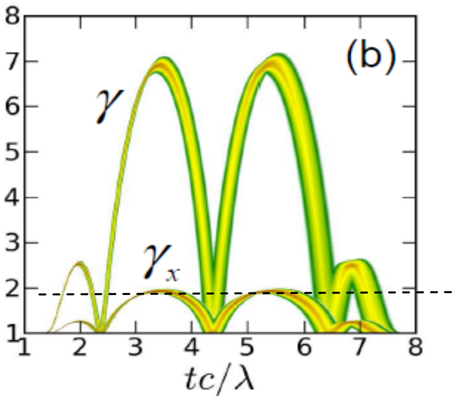
probe pulse

observer

$a_p = 0.1$

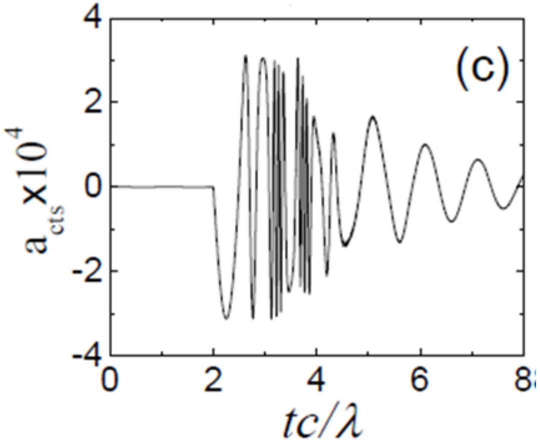
$a = 3.5$





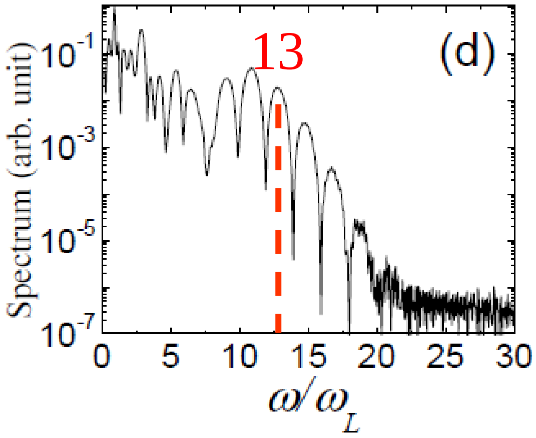
$\gamma_{x,\max} \approx 1.8$

without reflector



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

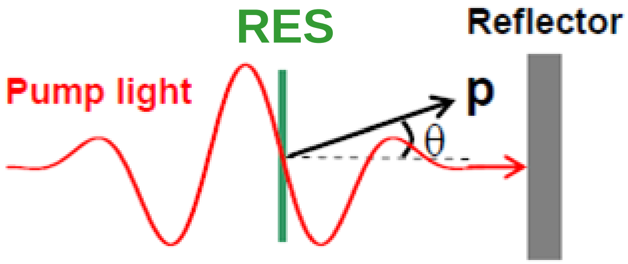
$4\gamma_{x,\max}^2 \approx 13$



How to restore full $4\gamma^2$ Doppler shift ?

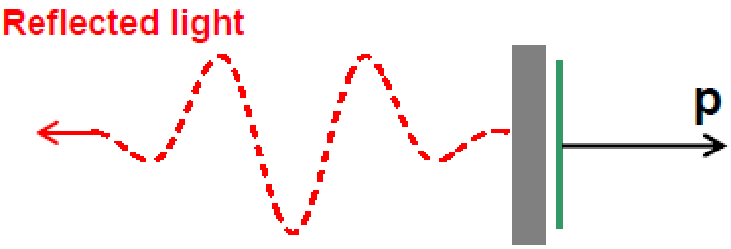
H.C. Wu, J. MTV et al. PRL 104, 234801 (2010)

Use additional reflector foil
that reflects laser field, but lets relativistic electrons pass



Canonical momentum conserved

$$p_\perp - eA_\perp = 0$$

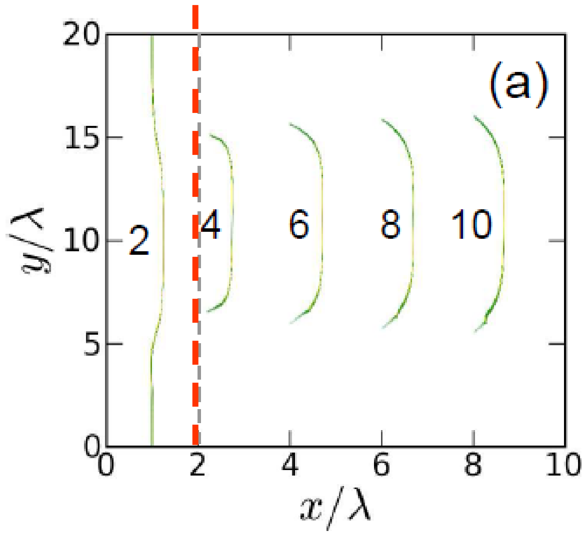


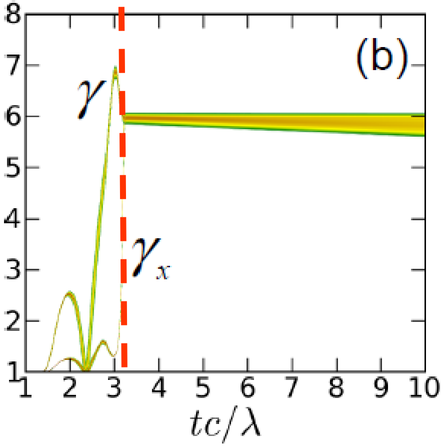
$$A_\perp \equiv 0 \ \ \text{(no field)}$$

$$p_\perp = 0$$

Reflector removes transverse momentum, restores $4\gamma^2$ shift

reflector

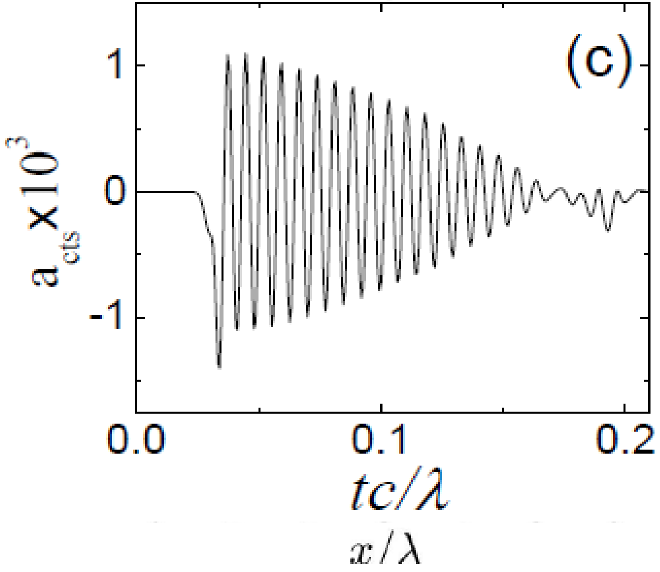


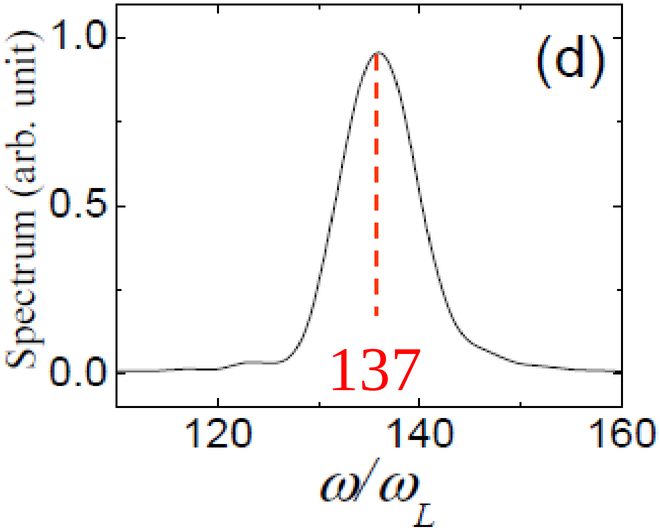


$\gamma \approx \gamma_x$

≈ 5.85

Backscattered signal
with reflector



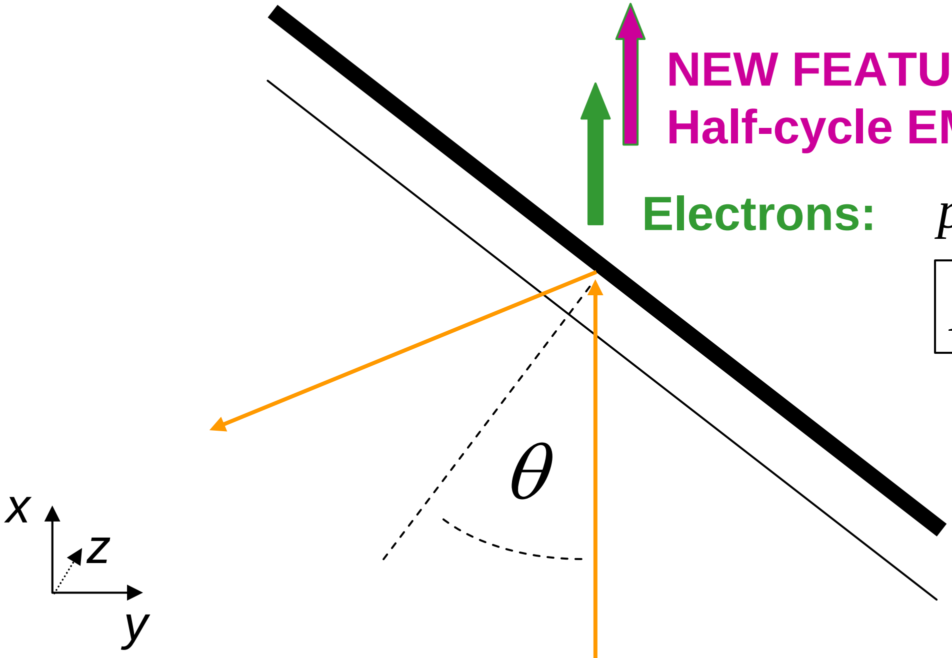


$\gamma \approx 5.85$

$4\gamma^2 \approx 137$

What happens for oblique incidence ?

H.C. Wu & J. Meyer-ter-Vehn, Nature Photonics 6, 304 (2012).



NEW FEATURE:
Half-cycle EMP radiated !!!

Electrons: $p_x \gg mc,\ p_z = 0$

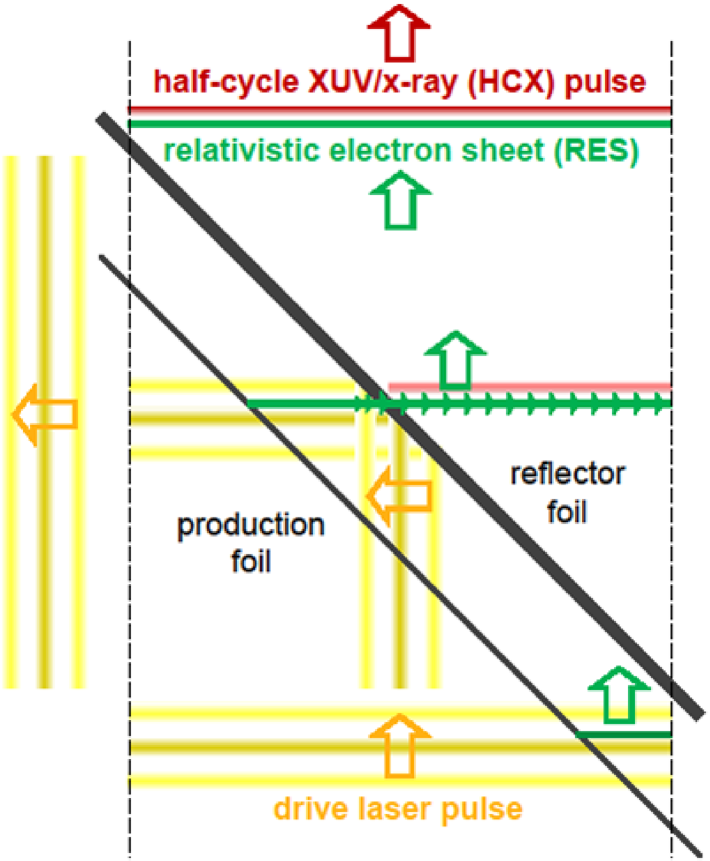
$$\boxed{p_y = mc\tan\theta}$$

s-polarized light (A_z)

Oblique incidence on double foil target (schematically)

1. Laser pulse drives electron sheet (RES) from production foil and

2. is separated from RES by reflector foil.

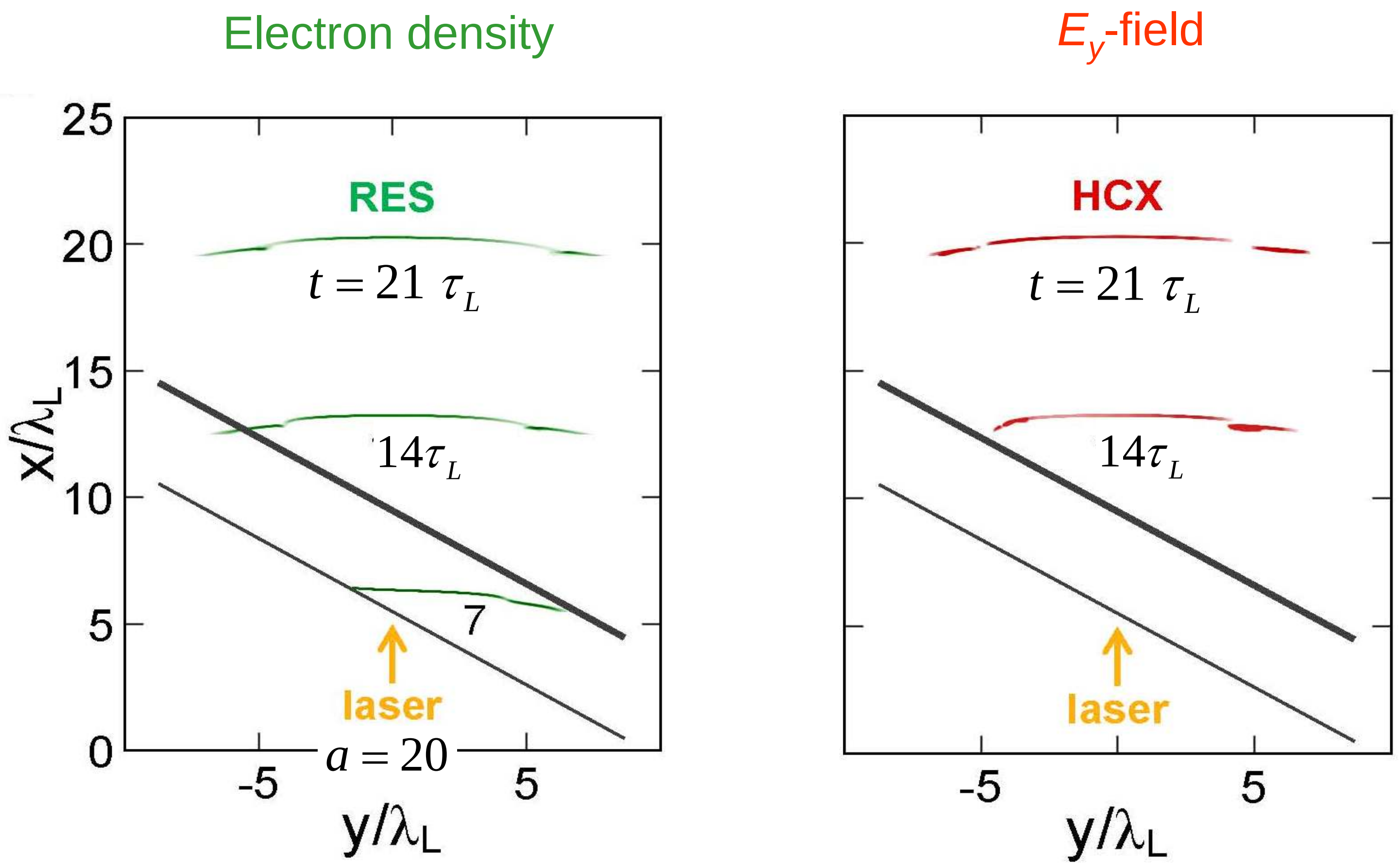


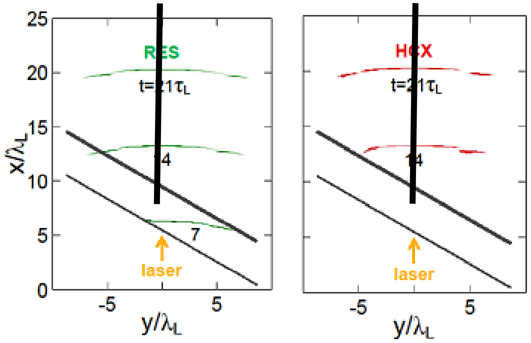
3. Passing reflector, transverse momentum of all electrons is switched to

$$p_z = 0$$
$$p_y = mc\tan\theta$$

4. Uniform current in y-direction radiates half-cycle pulse.

2D-PIC simulation of Relativistic Electron Sheet (**RES**) evolution and Half-Cycle X-ray (**HCX**) pulse

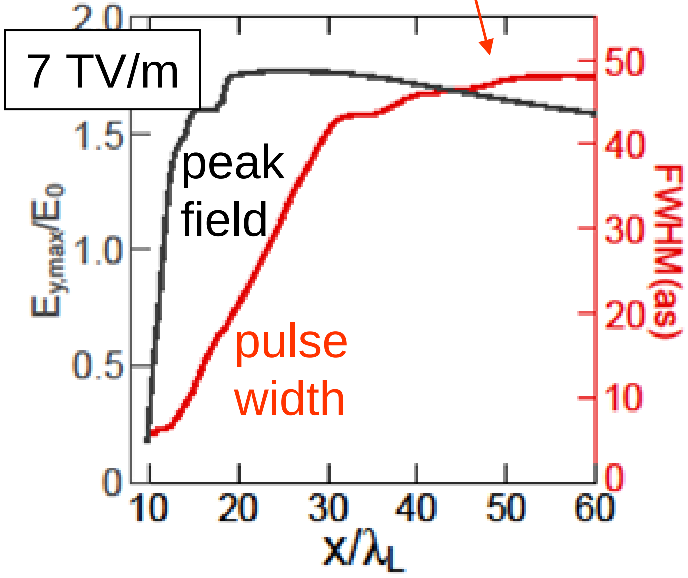




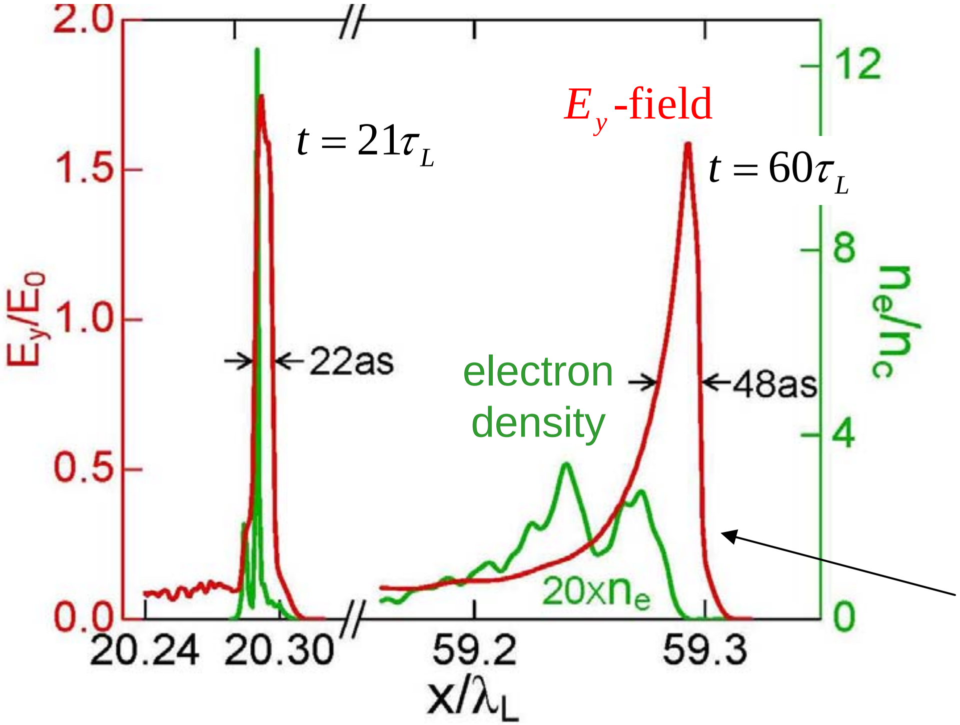
Simple scaling:

$$E_{y,\max} \approx E_s \gamma_x \sin\theta$$
$$\approx 11\ \text{TV/m}$$

$$T \approx mc \ln 2/(\gamma_{x0} e E_s)$$
$$\approx 52\ \text{as}$$


7 TV/m

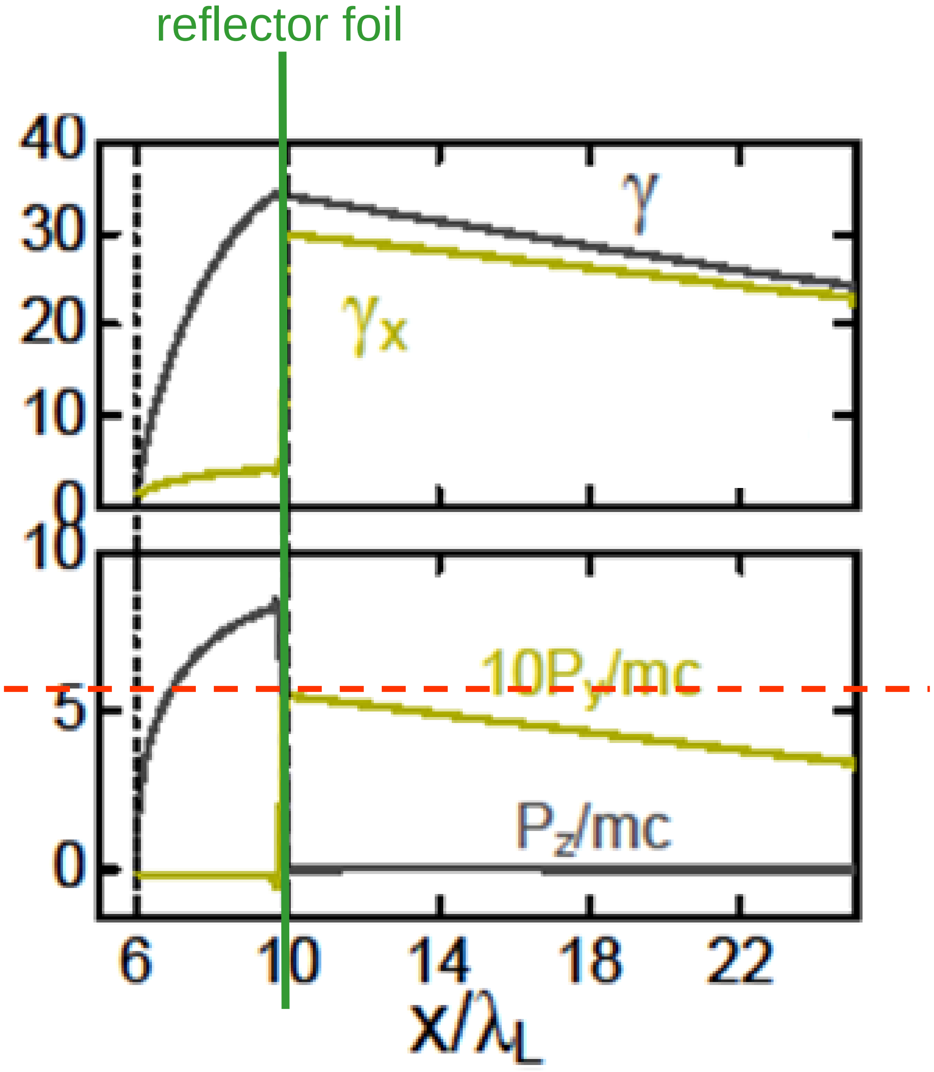
Central line-out



Notice extremely sharp front edge

$$\sim d/c \approx 10-100\ \text{as}$$

Reflector foil switches momenta



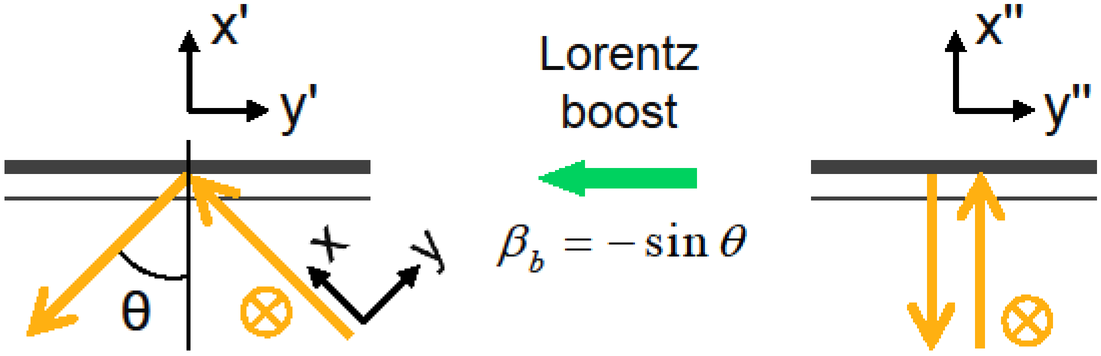
$$p_y / mc = \tan 30° = 0.57$$

Conservation of canonical momentum for oblique incidence

$$\hat{p}_y = \hat{p}''_y + \underbrace{(\hat{p}''_x - \gamma'')}_{\to 0 \ \text{for} \ \hat{p}''_x \gg 1} \sin\theta \approx \hat{p}''_y = \tan\theta$$

$$\hat{p}''_y = \tan\theta$$

$$\hat{p}''_z = 0$$



Lorentz boost

$$\beta_b = -\sin\theta$$

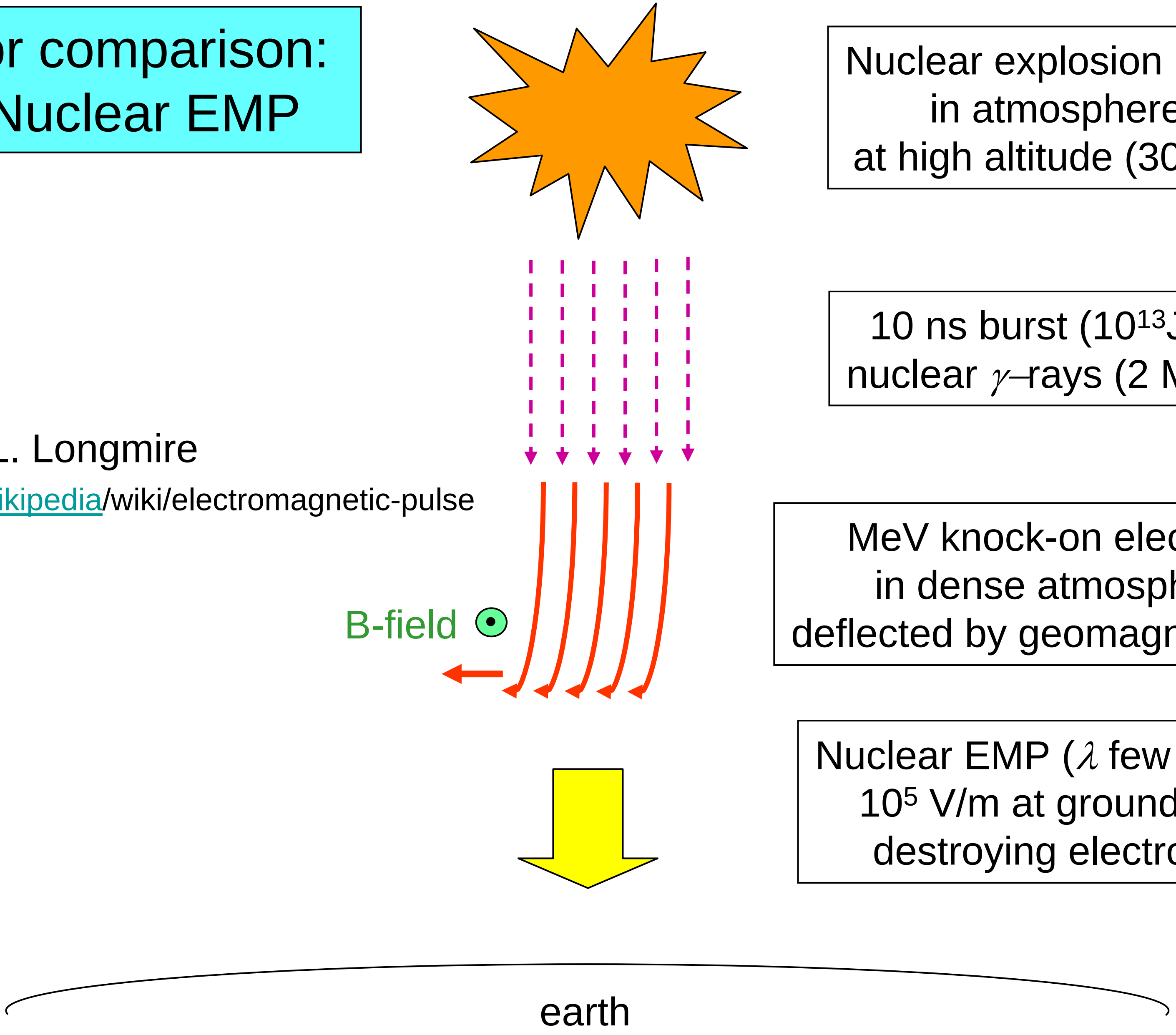
$$\hat{p}_y = 0$$

$$\hat{p}_z \equiv p_z / mc = a_z$$

$$\hat{p}''_y = \tan\theta$$

$$\hat{p}''_z = a_z$$

For comparison: Nuclear EMP



Nuclear explosion (1Mt)
in atmosphere
at high altitude (30 km)

10 ns burst (10^{13}J) of
nuclear γ–rays (2 MeV)

MeV knock-on electrons
in dense atmosphere
deflected by geomagnetic field

Nuclear EMP (λ few meters)
10^5 V/m at ground level
destroying electronics

See C.L. Longmire

http://en.wikipedia/wiki/electromagnetic-pulse

Conclusions

Few-cycle laser pulses may create relativistic electron sheets.

They may serve as relativistic mirrors for coherent Thomson scattering with $4\gamma^2$ Doppler shifts after passing a reflector foil.

For oblique incidence, unipolar electromagnetic pulses are generated with attosecond time structure.