Pair production and radiation reaction at high laser intensities

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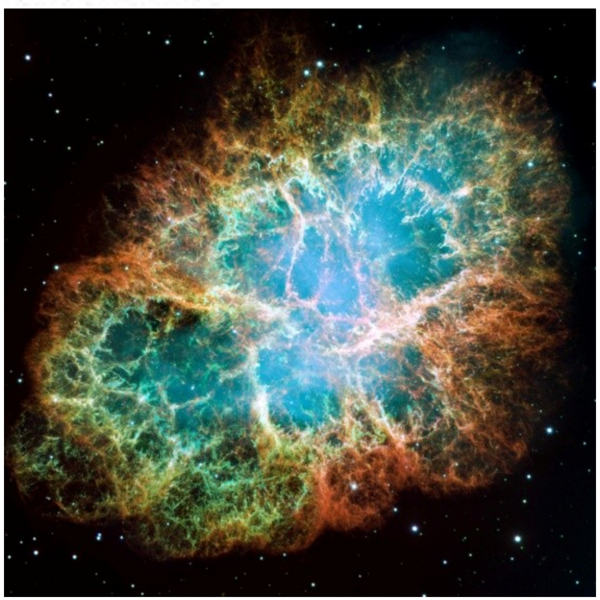
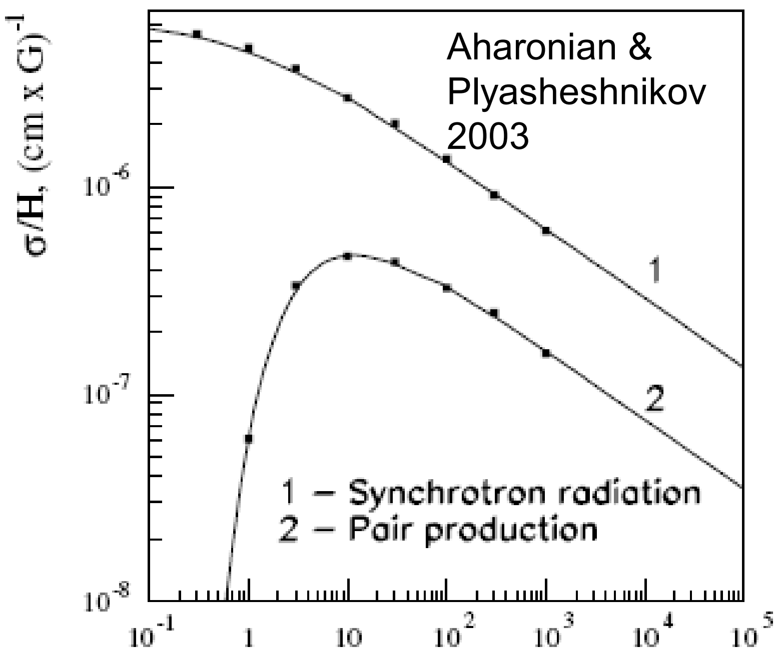
Science of Extremes

Q1. Can we recreate the conditions of a pulsar magnetosphere inside the laboratory?



PERSPECTIVE ON PAIR PRODUCTION

Pair production as a branch of synchrotron



$\gamma_e(B/B_{crit})$

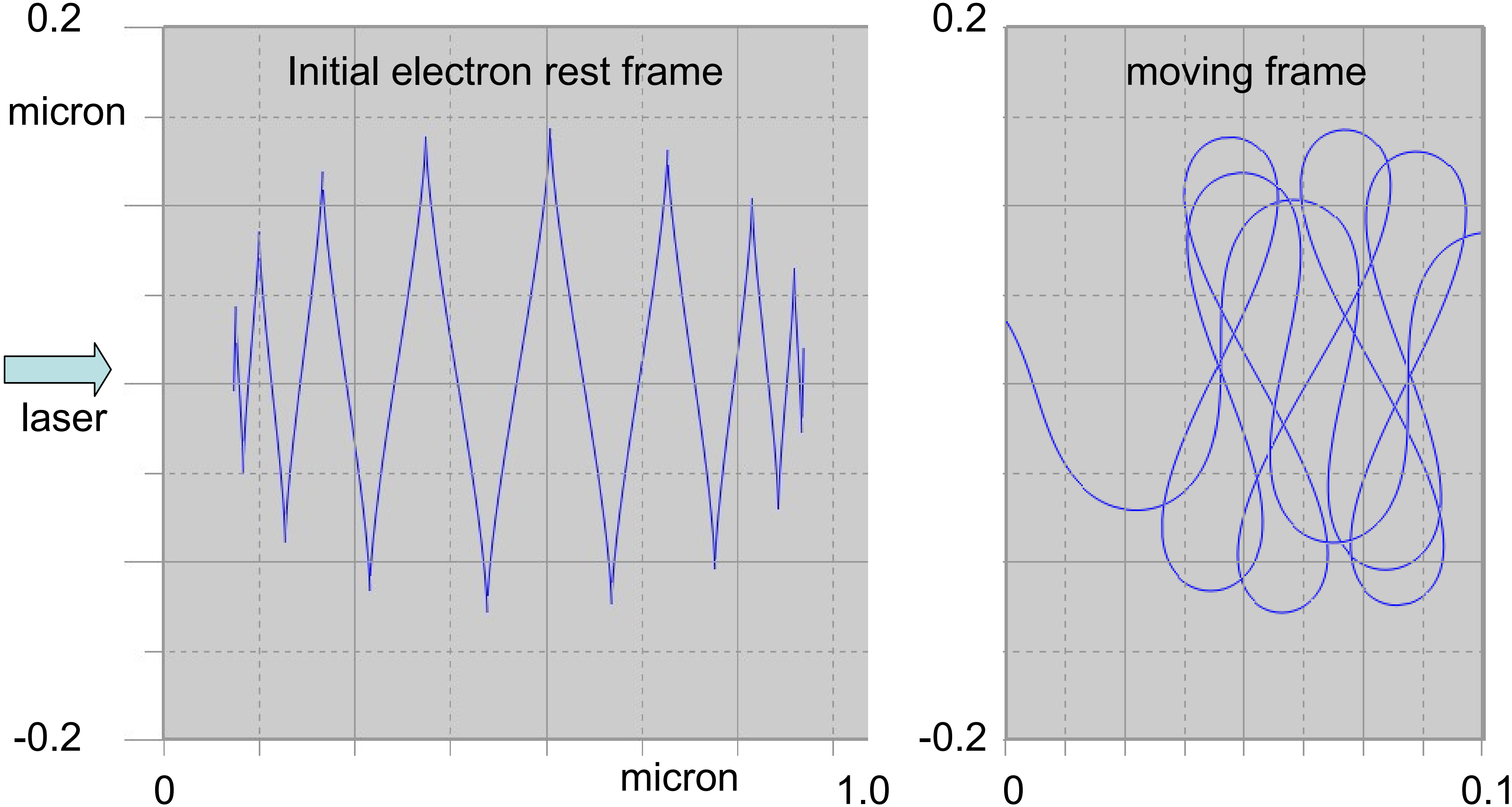
Schwinger field

Magnetic field given by laser

Oscillation in laser gives Lorentz factor γ_e

Not this simple!

Electron trajectory in planar vacuum laser wave $I=10^{18} Wcm^{-2}$



Circularly polarised vacuum plane wave ($\lambda = 1\mu m$)

Separate momentum (velocity) into

$p_{\parallel}$ ($v_{\parallel}$) in direction of wave propagation

$p_{\perp}$ ($v_{\perp}$) in perpendicular direction

wave amplitude $a = \frac{eA}{mc}$ ($a=1$ when $I = 2{\cdot}7 \times 10^{18}\ W\,cm^{-2}$)

Equation of motion without radiation reaction

$$\frac{dp_{\perp}}{dt} = e(E + v_{\parallel} \wedge B) \quad \Rightarrow \quad p_{\perp} = -a$$

$$\frac{dp_{\parallel}}{dt} = e\, v_{\perp} \wedge B \quad \Rightarrow \quad \frac{|p_{\parallel}|}{mc} = \frac{a^2}{2} \,, \quad \gamma = 1 + \frac{a^2}{2}$$

Electron carried along by wave

$$\frac{v_{\parallel}}{c} \rightarrow \frac{1}{1+2/a^2} \qquad \frac{v_{\perp}}{c} \rightarrow \frac{2}{a} \qquad \text{for large } a$$

Condition for pair creation

$$\gamma \left| \underset{\sim}{E} + \underset{\sim}{v} \wedge \underset{\sim}{B} \right|_T > cB_{crit} = \frac{cm\omega}{e} a_{crit}$$

Component transverse to electron velocity (T)

Schwinger field (B_{crit}, a_{crit})

For $1\mu m$ light $a_{crit} = 4 \times 10^5$

$(I_{crit} = 4.5 \times 10^{29}\ Wcm^{-2})$

For large a, $\gamma = 1 + \frac{a^2}{2}$, $E = \frac{cm\omega}{e} a$

Suggests condition is $\frac{a^3}{2} > a_{crit}$ $(I > 2.4 \times 10^{22}\ Wcm^{-2})$

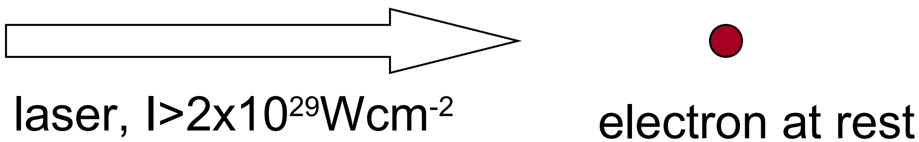
BUT $\underset{\sim}{E}$ and $\underset{\sim}{v} \wedge \underset{\sim}{B}$ nearly cancel

($\underset{\sim}{v} \wedge \underset{\sim}{B}$ nearly anti-parallel to $\underset{\sim}{E}$)

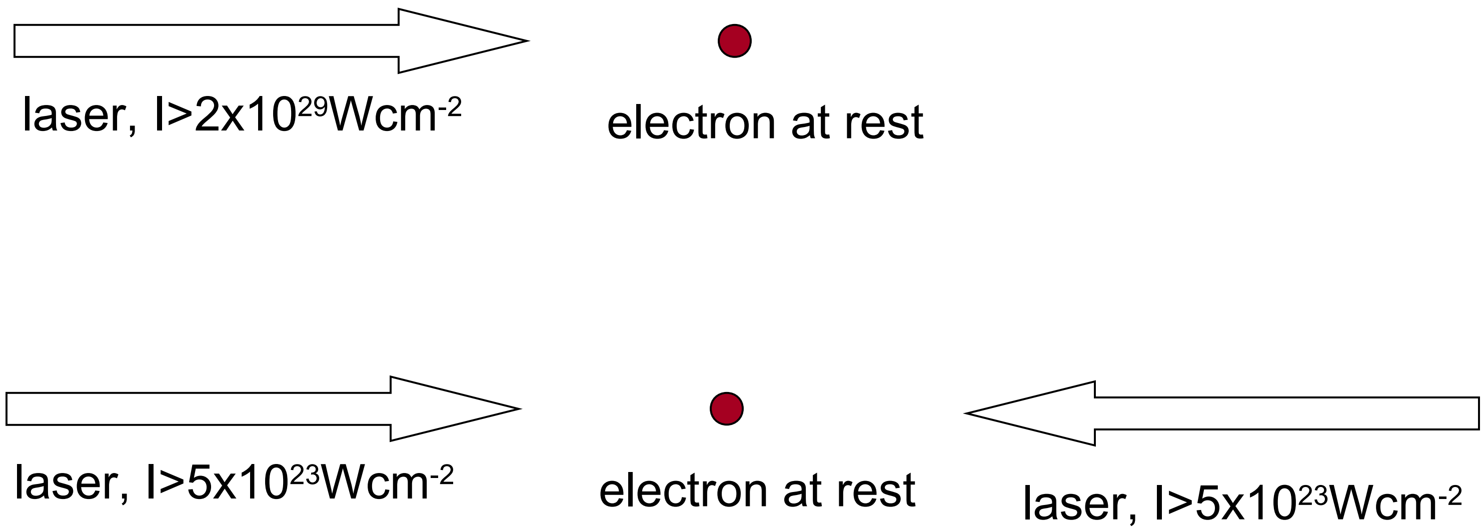
$$\Rightarrow \left| \underset{\sim}{E} + \underset{\sim}{v} \wedge \underset{\sim}{B} \right|_T \rightarrow \frac{8}{a^2} \left| \underset{\sim}{E} \right| \quad \text{for } a \gg 1$$

ACTUAL CONDITION: $a > \frac{1}{\sqrt{2}} a_{crit}$ $(I > 3 \times 10^{29}\ Wcm^{-2})$

How to satisfy $\gamma_e B > 4.4 \times 10^4 \mathrm{GG}$ or $\gamma_e E > 1.3 \times 10^{18} \mathrm{V/m}$



How to satisfy $\gamma_e B > 4.4\times 10^4\,\mathrm{GG}$ or $\gamma_e E > 1.3\times 10^{18}\,\mathrm{V/m}$



Analytic solution for two counter-propagating beams

Equal intensity
Circular polarisation
Nodes where B=0

Counter-propagating laser beams (circular polarisation)

$E_x = E_0 \cos kz \cos \omega t \qquad B_y = -\frac{E_0}{c} \sin kz \sin \omega t$

Nodes where $B = 0$ $(kz = n\pi)$

e^- subject only to electric field

$\Rightarrow \frac{p_\perp}{mc} = a \quad , \quad p_\parallel = 0$

$\gamma |E + v \wedge B|_T \propto a^2$

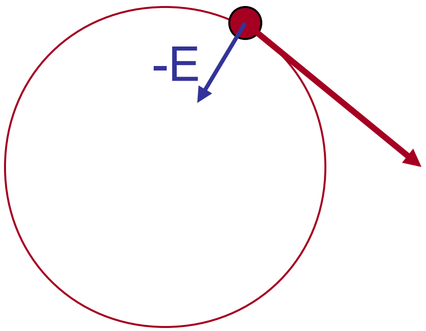
Suggests pair creation for $a > \sqrt{a_{crit}}$ $(I > 3 \times 10^{23}\, W cm^{-2})$

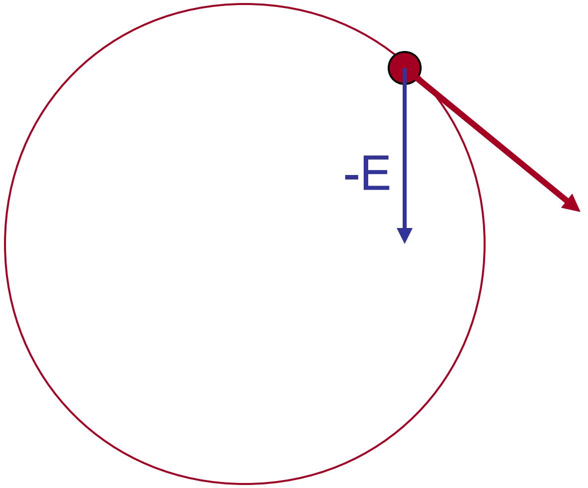
Advantages of collider geometry

HOWEVER: this neglects radiation reaction.

SPECIAL CASE: solved analytically

Electron motion at B=0 node of standing wave
circular polarisation





Medium intensity
Small radiation reaction

High intensity
Large radiation reaction

Equivalent to motion in mag field (synchrotron)
Use Erber (1966) cross-sections: pair production

Include radiation reaction

$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \mathbf{v}\wedge\mathbf{B}\right) - \frac{2}{3}\gamma^2 \frac{\mathbf{v}}{c}\,\sigma_T \varepsilon_0 \left|\mathbf{E} + \mathbf{v}\wedge\mathbf{B}\right|_T^2$$

radiation reaction

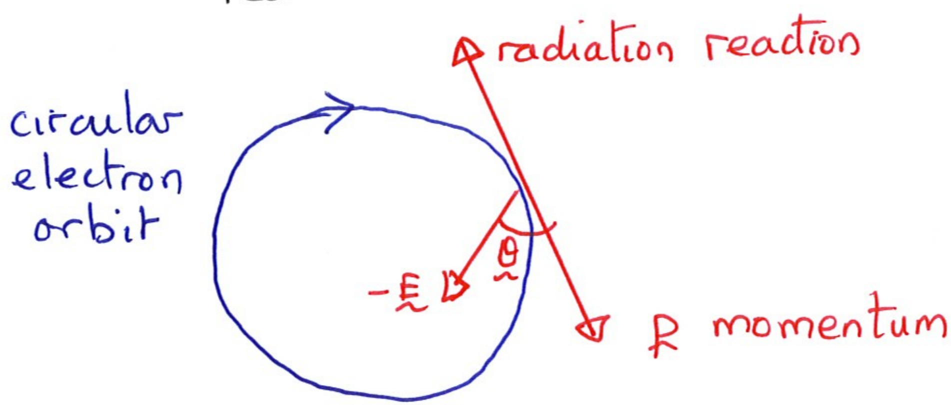
Circular polarisation, counter-propagating beams

→ stationary wave

At node where $\mathbf{B} = 0$

$$\boldsymbol{\omega}\wedge\mathbf{p} + \frac{2}{3}\gamma\,\mathbf{p}\,\frac{\sigma_T \varepsilon_0 E^2}{mc} = -e\,\mathbf{E}$$

circular rotation | radiation reaction | driving laser field



Pair creation if $\eta > 1$

$$\eta = \frac{\gamma E \sin\theta}{E_{crit}}$$

θ ← angle between $\mathbf{p}$ and $\mathbf{E}$

E_{crit} ← Schwinger field

Balancing forces, equation of motion

in units of $10^{24}\ \mathrm{W\,cm^{-2}}$

$$2.75\,\eta^4 + 0.28\,\eta = I_{24}$$

radiation reaction — rate of change of momentum — laser driving field

Weak rad^n reaction, $I < 10^{23}\ \mathrm{W\,cm^{-2}} \Rightarrow \eta = 3.6\,I_{24}$

Strong rad^n reaction, $I > 10^{24}\ \mathrm{W\,cm^{-2}} \Rightarrow \eta = 0.78\,I_{24}^{1/4}$

$\eta > 1$ for pair production
begins in range $10^{23} - 10^{24}\ \mathrm{W\,cm^{-2}}$

Pair production rate (pairs per electron per laser period)

$$\tau_{tr} = 0.06\, I_{24}^{1/2}\, \eta^{1/4} \exp\left(-\frac{8}{\sqrt{3\eta}}\right) \quad \text{for } \eta < 1$$

Characteristic numbers for $I = 3.3 \times 10^{23}$ W cm^{-2}

$\eta = 0.5$ ($\eta > 1$ for pair creation, $\gamma|E + v \wedge B|_T > E_{crit}$)

Each electron produces 3×10^{-5} pairs in each laser period

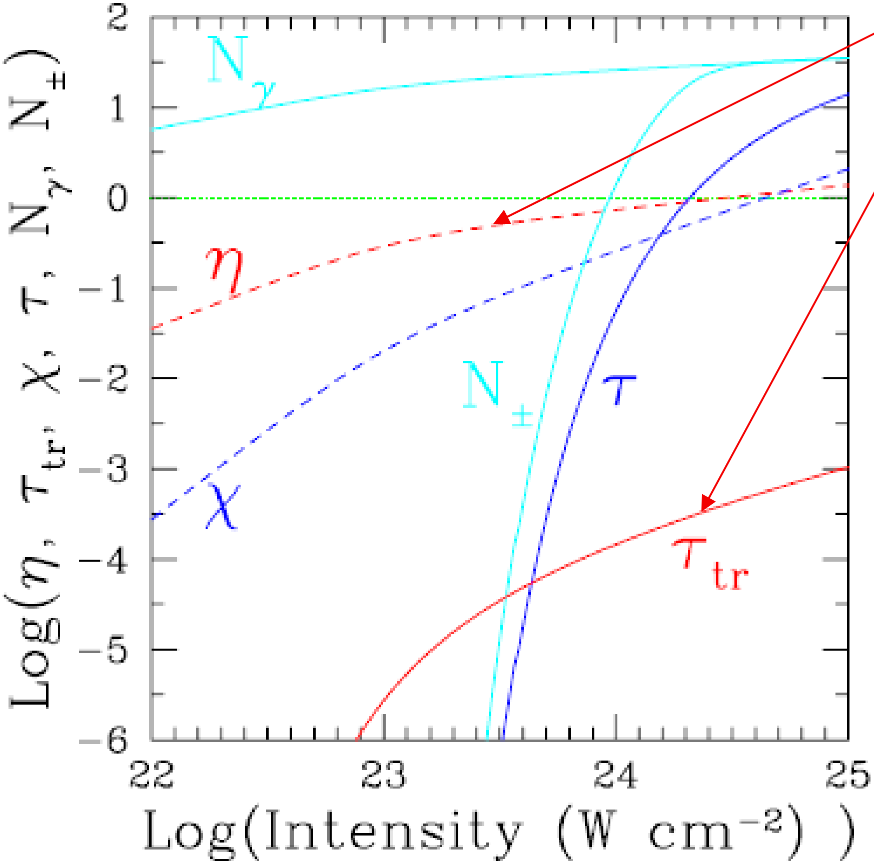
Radiated energy (γ-rays) is 123 kW per electron

Laser beam damped in time $180\, n_{21}^{-1}$ fsec

↑ density in 10^{21} cm^{-3}

Number of pairs is 7×10^{4} per Joule of laser energy

Counter-propagating circularly polarised beams
Electron motion at *B*=0 node of standing wave



$\eta = \gamma|E+vxB|_{perp}/E_{crit}$

τ_{tr} = number of pairs produced per electron per laser period by trident process

Bell & Kirk, PRL 2008

So far: trident process

pairs produced by direct interaction between oscillating electron and laser field

At intensity $\sim 10^{24}\ \mathrm{W\,cm^{-2}}$

real photon process dominates

electron + laser field → real γ-ray photon

γ-ray + laser field → e^+/e^- pair

→ one pair per electron per laser period

→ cascade/avalanche

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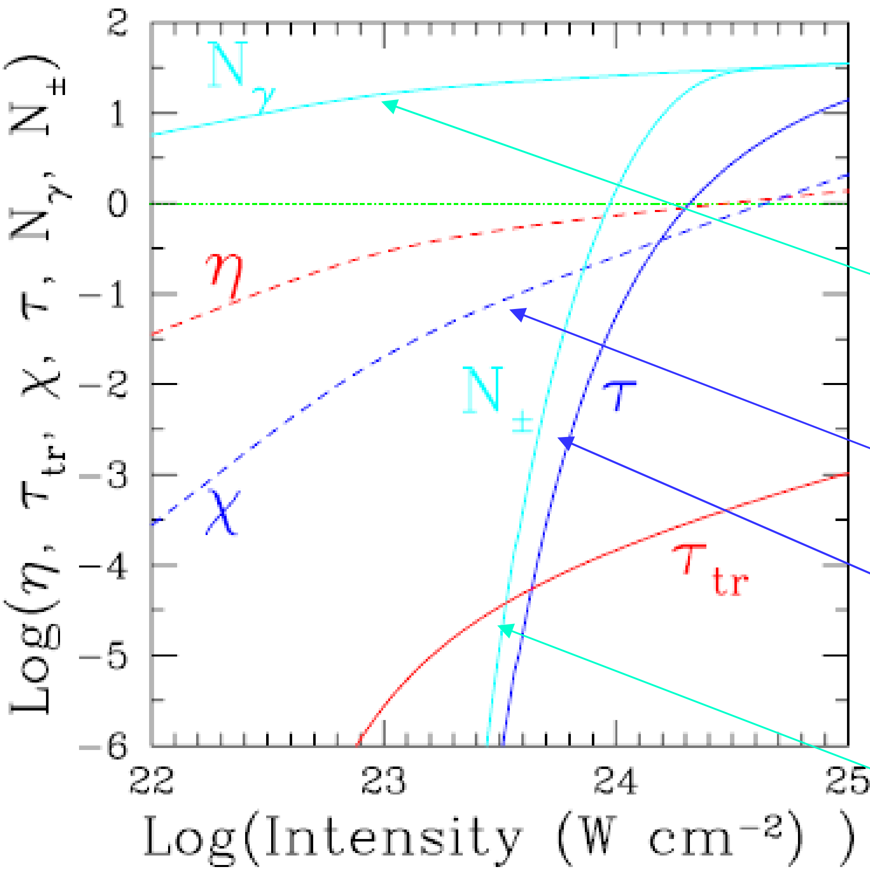
Electron motion at B=0 node of standing wave



N_γ = number of photons produced per electron per laser period

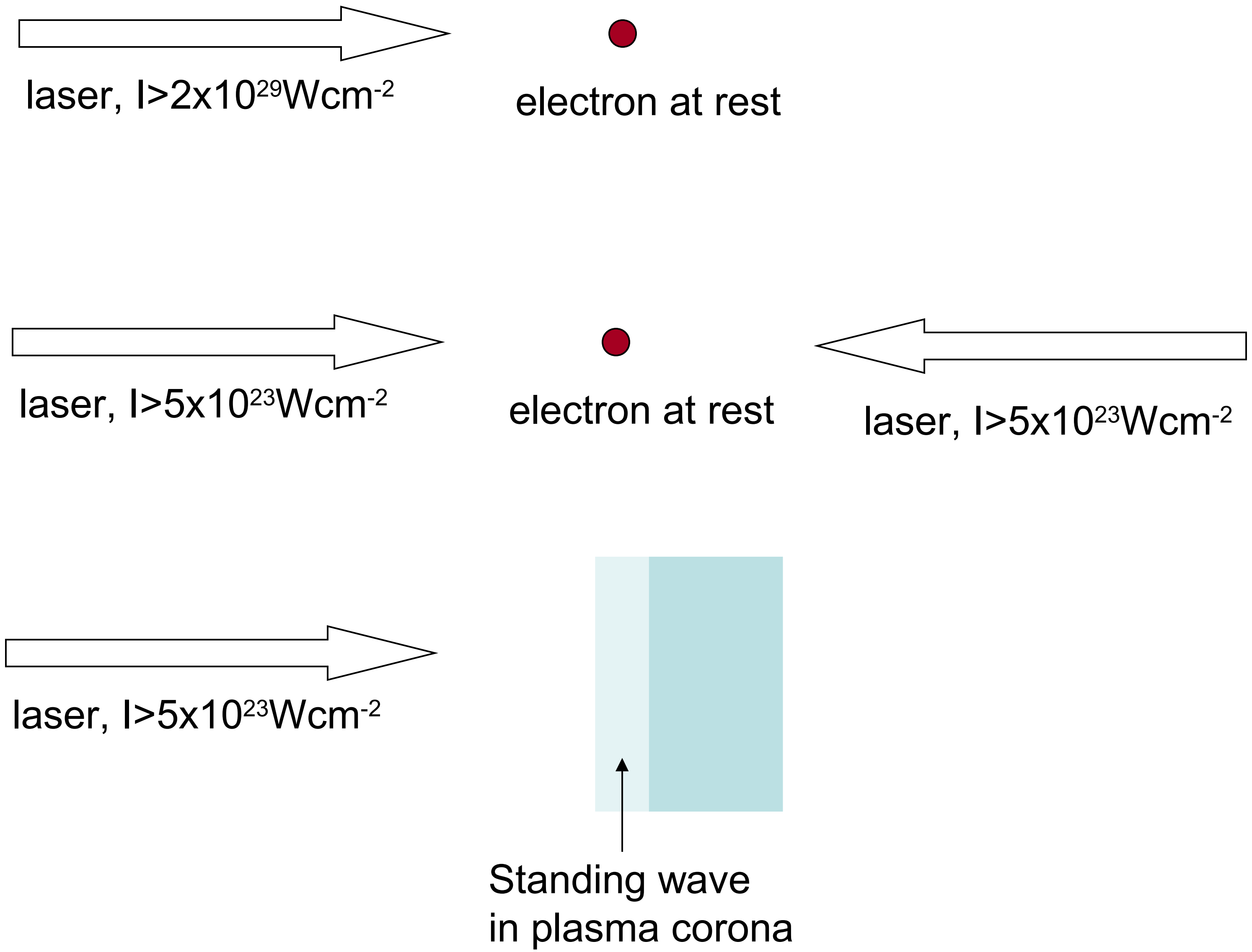
χ = equivalent for photons of η

τ = photon optical depth in one wavelength

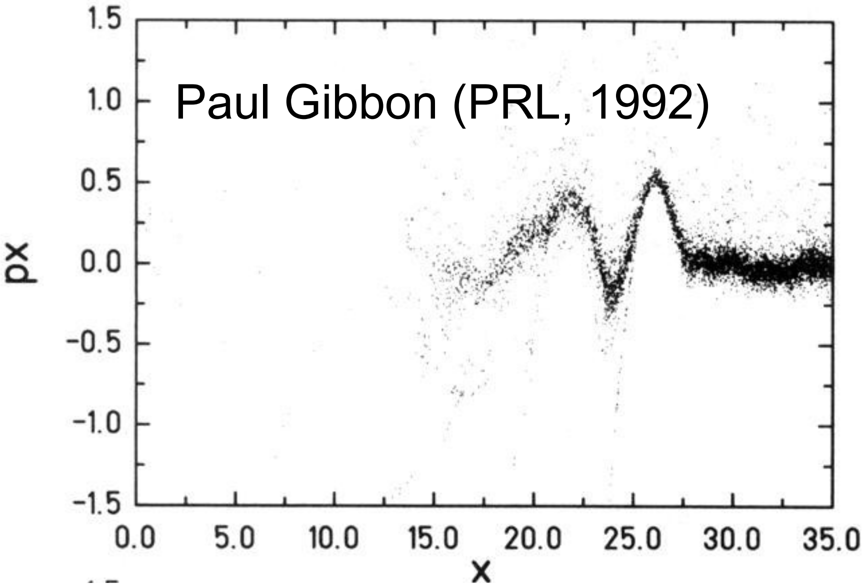
$N_{+/-}$ = number of pairs produced per electron per period in 1μm^3 plasma

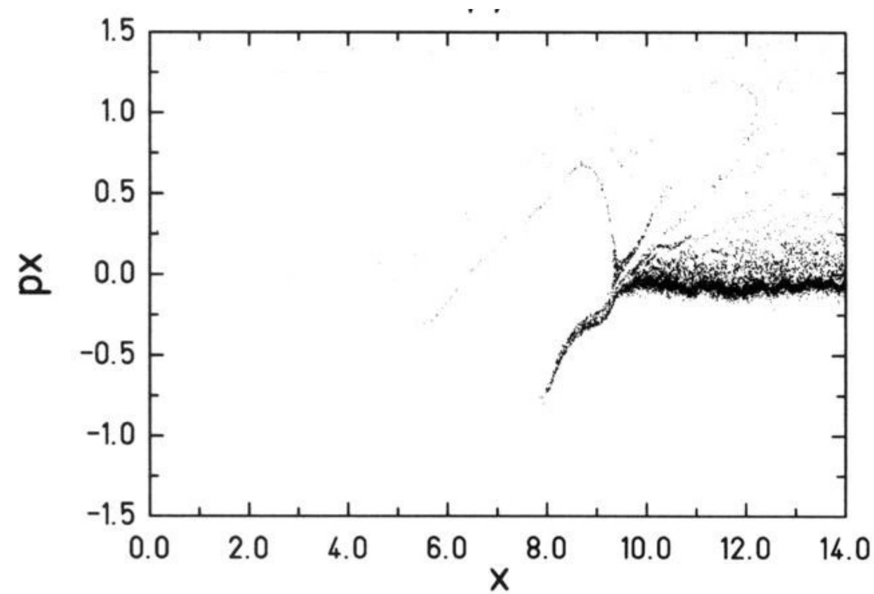
Bell & Kirk, PRL 2008

How to satisfy $\gamma_e B > 4.4 \times 10^4\,\mathrm{GG}$ or $\gamma_e E > 1.3 \times 10^{18}\,\mathrm{V/m}$

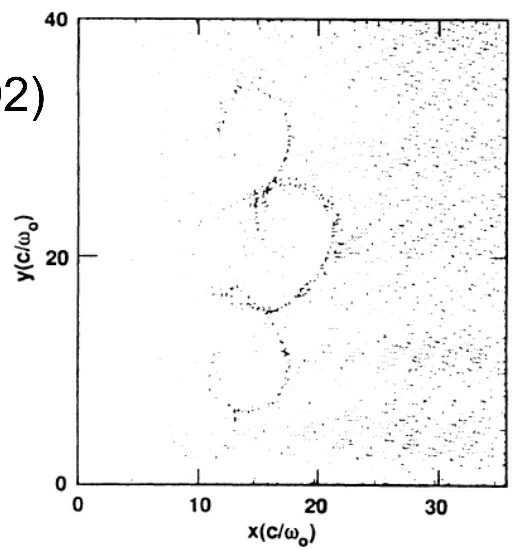


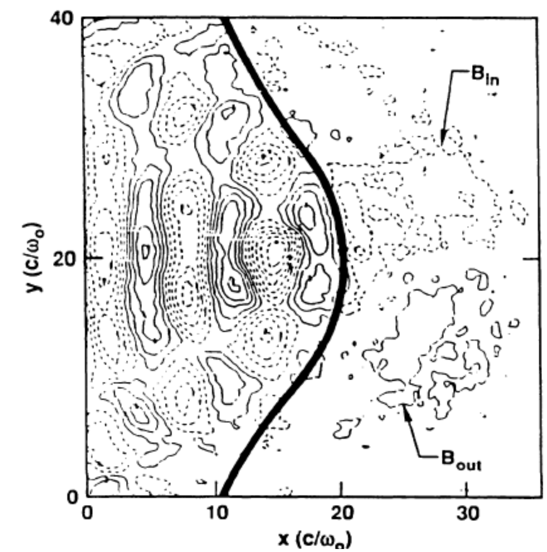
Particle-in-cell modelling of laser-plasma interactions





Wilks et al (PRL, 1992)





Reflected laser beam highly distorted (Baeva et al)

BAEVA, GORDIENKO, AND PUKHOV PRE 74 046404 (2006)

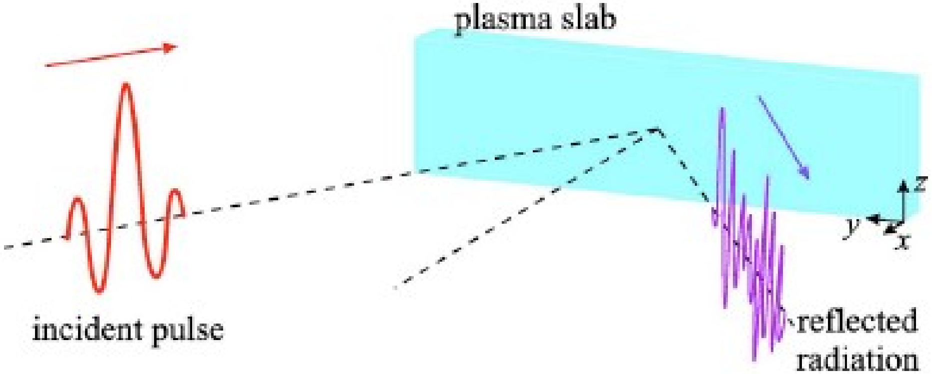


FIG. 1. (Color online) Geometry of the problem. The laser pulse is moving towards the overdense plasma slab, x is perpendicular to the surface, and y and z are parallel to it.

Reflected laser waveform contains spikes

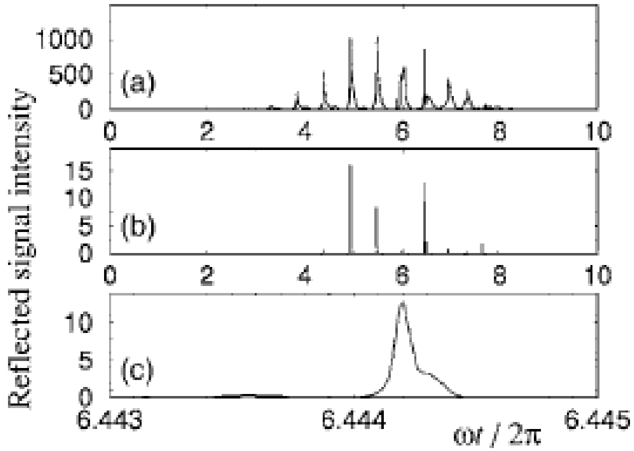


FIG. 8. Zeptosecond pulse train: (a) temporal structure of the reflected radiation; (b) zeptosecond pulse train seen after spectral filtering; and (c) one of the zeptosecond pulses zoomed (its FWHM duration is about 300 zs).

Spikes seen as high harmonics

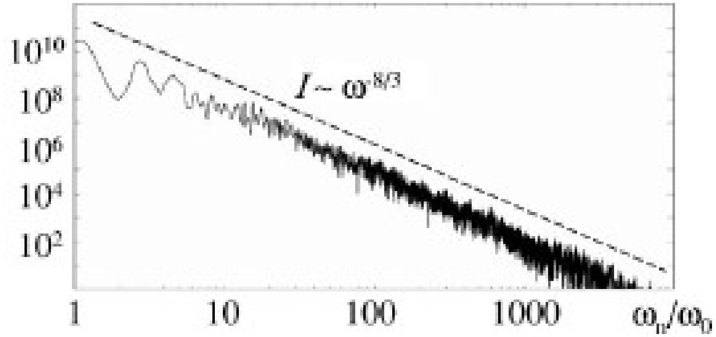
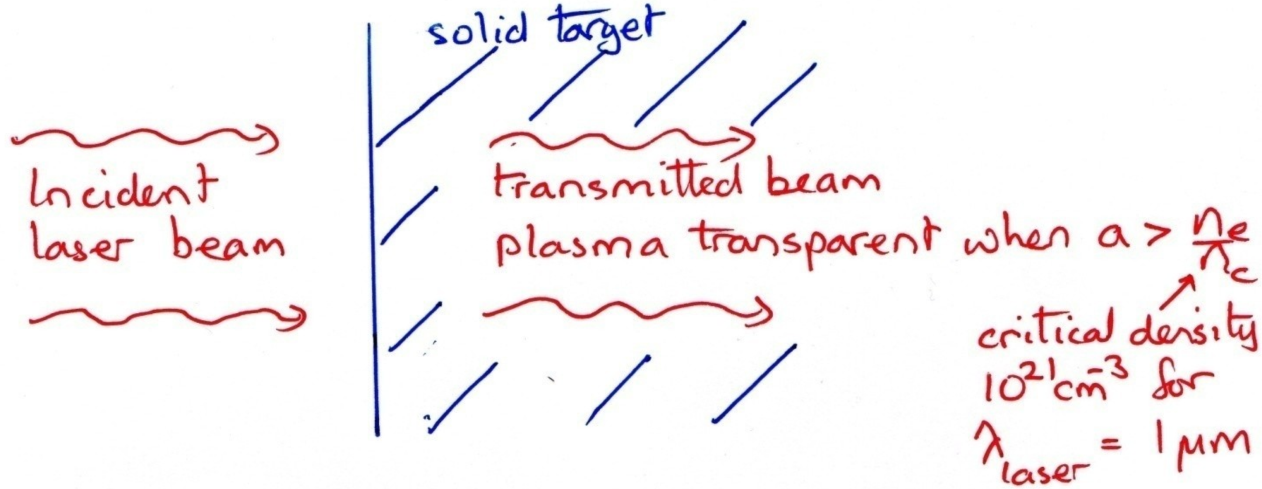


FIG. 7. Spectra of the reflected radiation for the laser amplitude a_0=20 and the plasma density N_e=30N_{cr}. The broken line marks the universal scaling $I \propto \omega^{-8/3}$.

Transparent solid targets



'Linear' dispersion relation

$$\omega^2 = \frac{\omega_{pe}^2}{a} + k^2 c^2$$

$$\omega_{pe}^2 = \frac{ne^2}{\varepsilon_0 m}$$

a represents relativistic mass increase

$$m \to \gamma m = am$$

$$n_c \to a n_c$$

Solid transparent for $I \gtrsim 3 \cdot 10^{23}$ W cm^{-2}

Low density foam transparent at lower intensities

'Overdense propagation'

CONCLUSIONS

Next generation lasers enter radiation-dominated, pair-production regime

Answer real questions about astrophysics: pulsar /AGN winds

Connects plasma physics with non-linear QED

Probe radiation losses short of radiation-dominated regime
Spectrum/direction of 10-100MeV photons

Need to integrate with PIC simulation

See poster by John Kirk