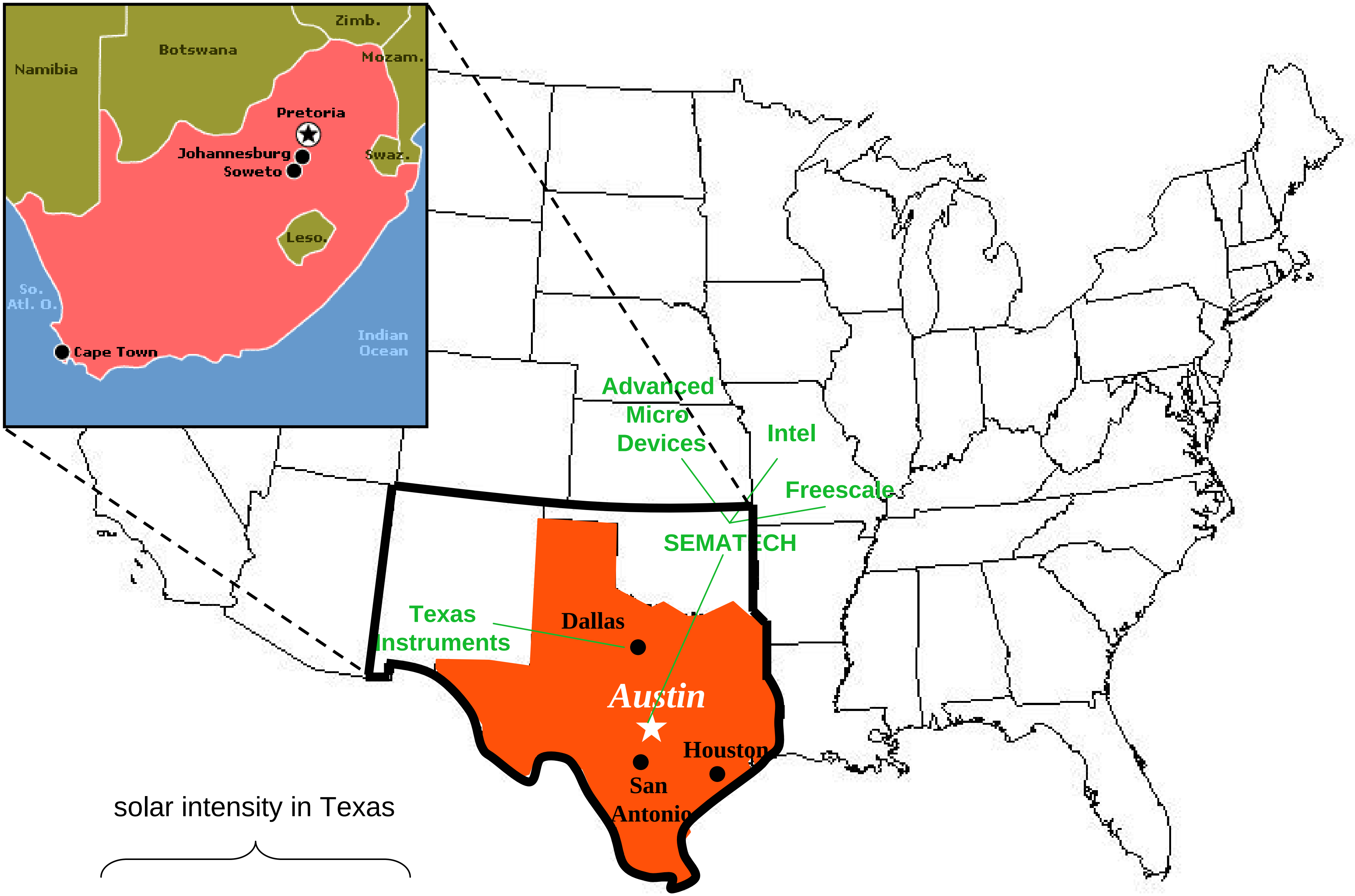
1.2×10^6 km^2



$$\overbrace{1.4 \times 10^3\ \mathrm{W/m^2}}^{\text{solar intensity in Texas}} \times \mathbf{7 \times 10^5\ km^2} = 1\ \text{petawatt}$$

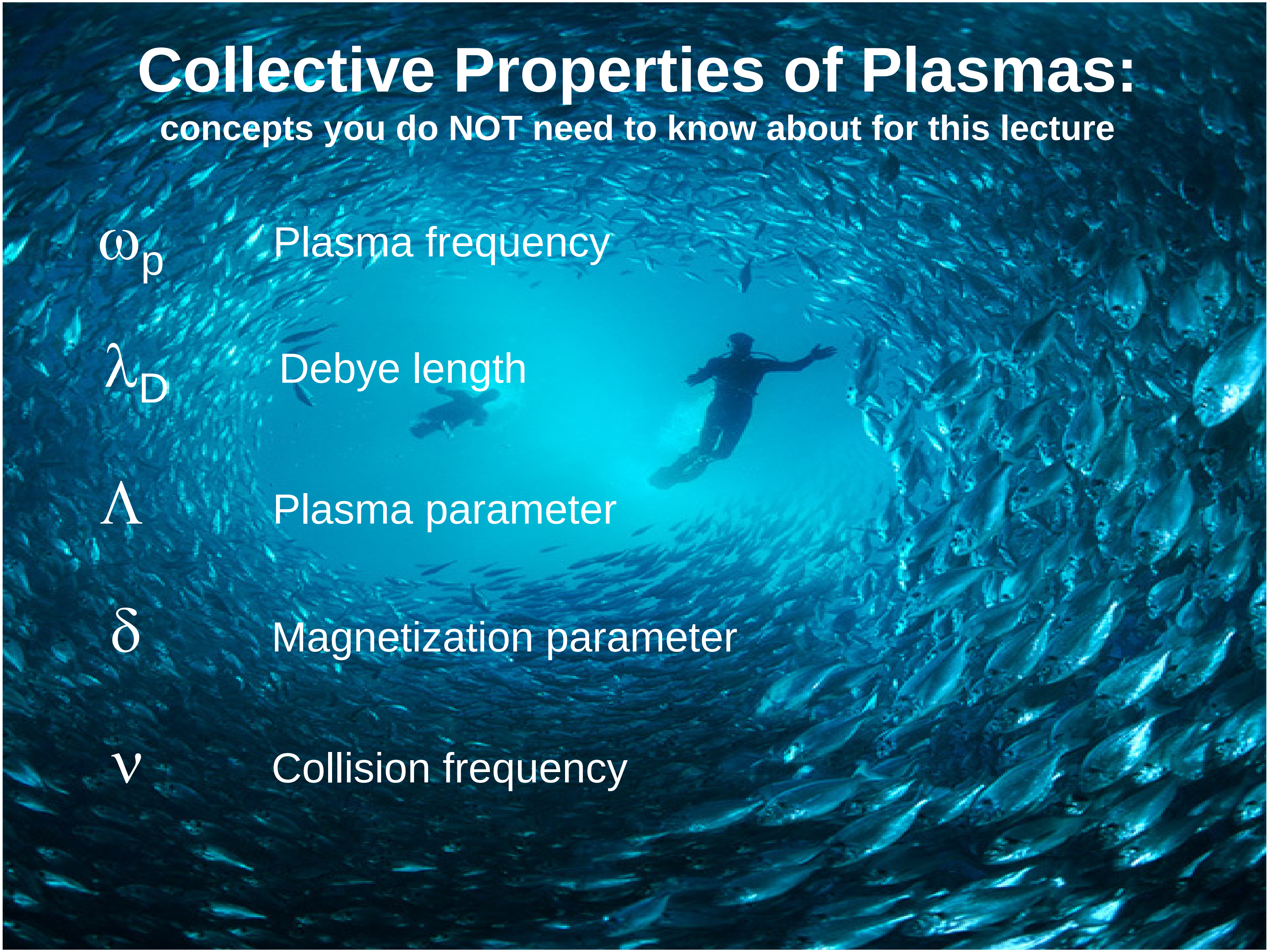
Lasers and Accelerators: Particle Acceleration with High Intensity Lasers
Stellenbosch Institute of Advanced Study Stiαs
13 January 2009

Laser-plasma experiments: lecture 1 of 4

Who needs plasma?

Observations of intense laser interaction with, and radiation from, individual electrons

Mike Downer
University of Texas-Austin



Collective Properties of Plasmas:

concepts you do NOT need to know about for this lecture

ω_p	Plasma frequency
λ_D	Debye length
Λ	Plasma parameter
δ	Magnetization parameter
ν	Collision frequency

Physics you <u>will</u> need to know about for this lecture:

$$\vec{F} = m\vec{a}$$

$$q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right)$$

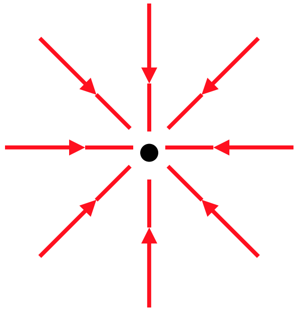
$$\gamma m_0$$

where $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$

and $m_0c^2 = 0.51$ MeV

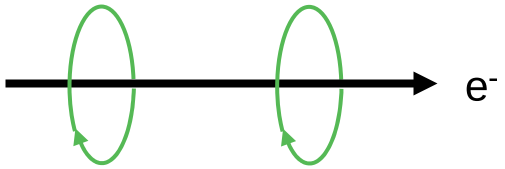
Laser Radiation & Electron Acceleration

Stationary Electrons → Electrostatic Fields

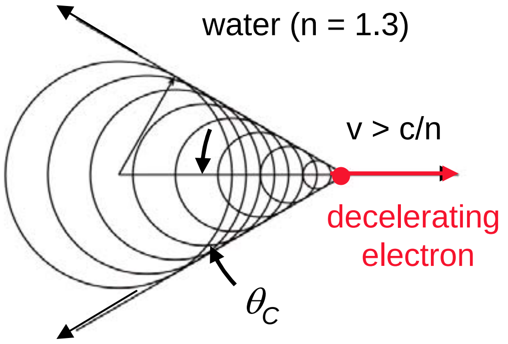


Steady Currents → Magnetostatic Fields

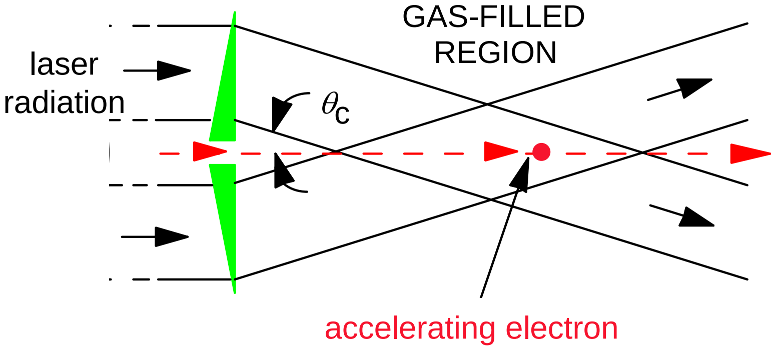
(electrons moving at constant velocity)



Accelerating Electrons ⟺ Electromagnetic Radiation



Cerenkov Radiation

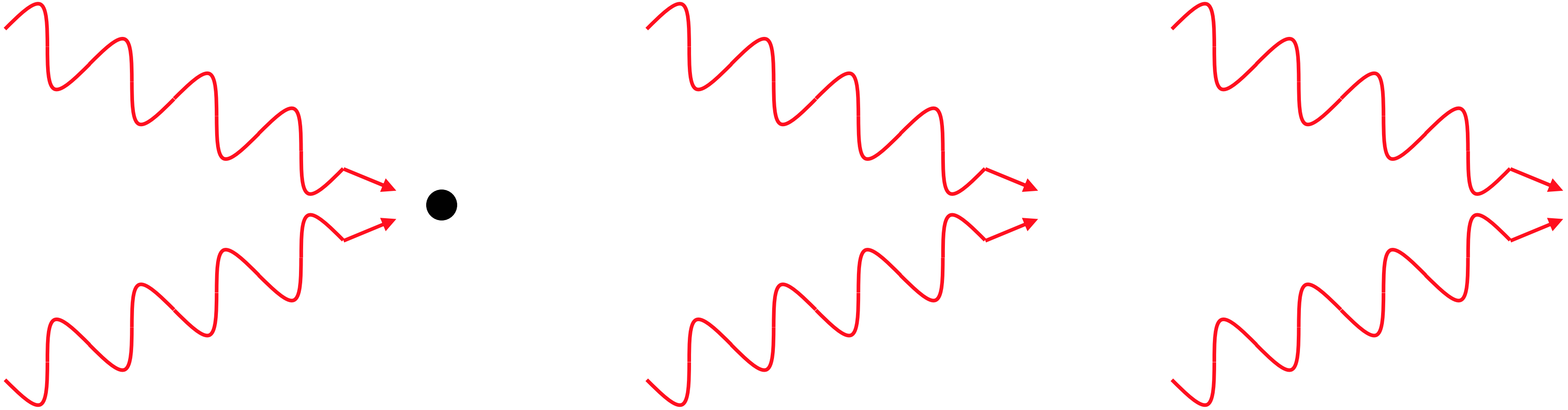


Inverse Cerenkov Accelerator

Any process that generates radiation may be inverted to accelerate charged particles

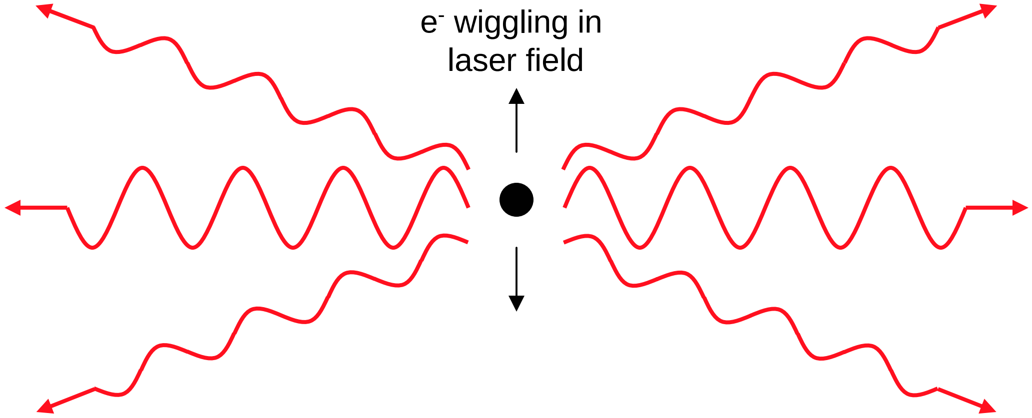
I will discuss 2 types of experiments

I. Direct Laser Acceleration (DLA) of electrons



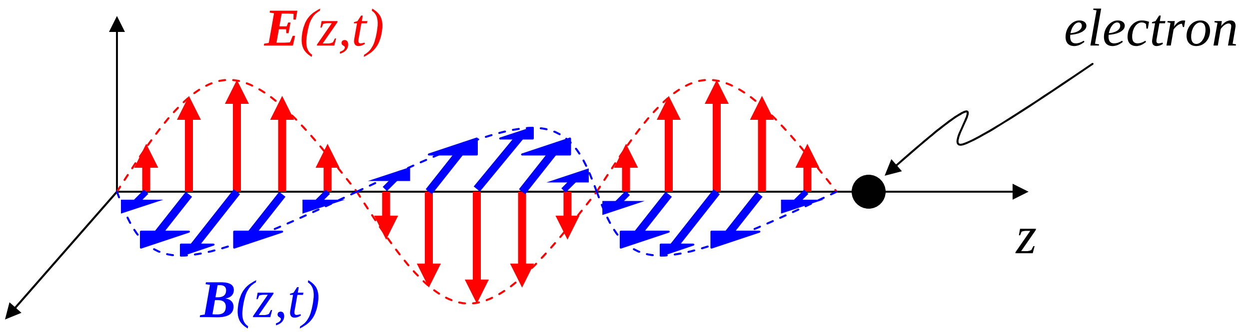
II. Radiation from accelerated electrons

- Thomson, Compton scatter and synchrotron radiation



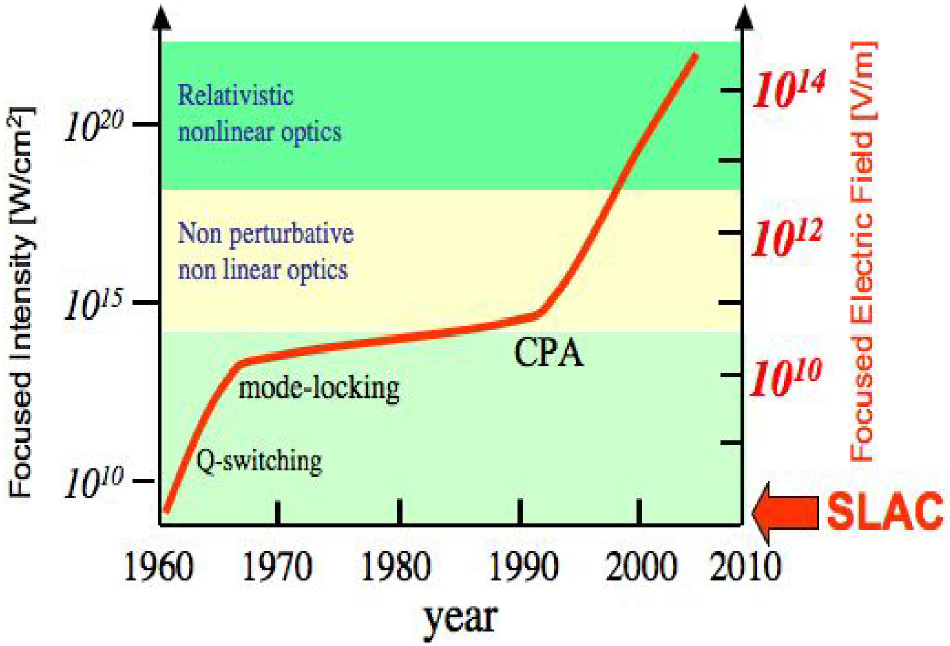
selected experiments are illustrative, not comprehensive

I. Direct Laser Acceleration of Electrons in Vacuum?



Good idea

Modern lasers provide unprecedented accelerating fields (larger than SLAC)



Dumb idea

EM waves wiggle the electron sideways; they don't accelerate it linearly

$$\vec{F} = m\vec{a}$$

$$e\vec{E} = m_0 \frac{d\vec{v}}{dt} \quad \text{and} \quad \vec{E} = \vec{E}_0 e^{ik_0 z - i\omega t} \; *$$

$$\therefore \frac{d\vec{v}}{dt} = \frac{e}{m}\vec{E}_0 e^{ikz - i\omega t}$$

↕ e^- motion at fixed z

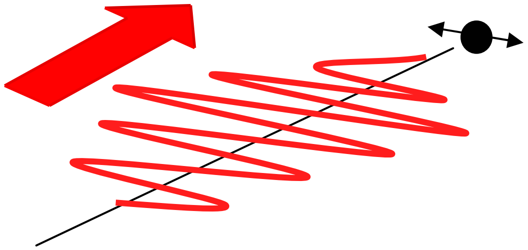
*Neglecting **v** × **B** and relativistic effects

Lawson-Woodward Theorem:

Mathematical proof that DLA is a dumb idea?

J.D. Lawson, *IEEE Trans. Nucl. Sci.* **NS-26**, 4217, 1979

The net energy gain of an electron interacting with an electromagnetic field in vacuum is zero.



The theorem assumes that:

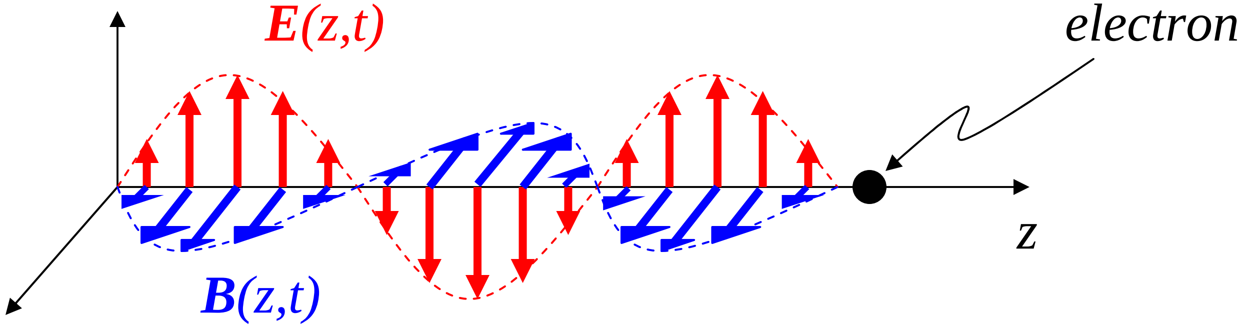
(i) the laser field is in vacuum with no walls or boundaries present,

(ii) no static electric or magnetic fields are present,

(iii) the region of interaction is infinite,

(iv) ponderomotive effects (nonlinear forces, *e.g.* **v** x **B** force) are neglected.

Exploit v × B force at “relativistic” light intensity to accelerate electrons longitudinally?

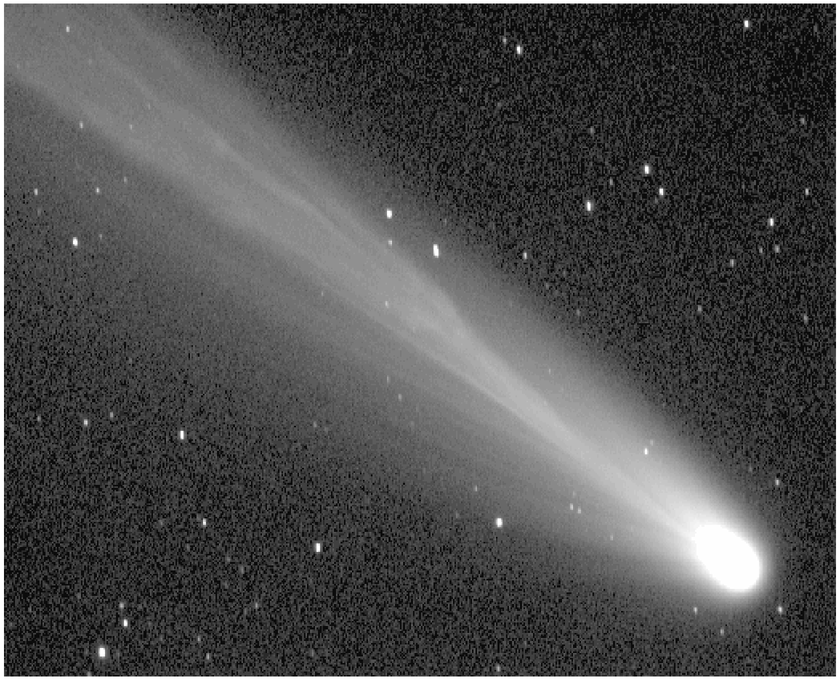


$$\vec{F} = m\vec{a}$$

$$e\vec{E} + \frac{\vec{v}}{c} \times \vec{B} = m\frac{d\vec{v}}{dt}$$

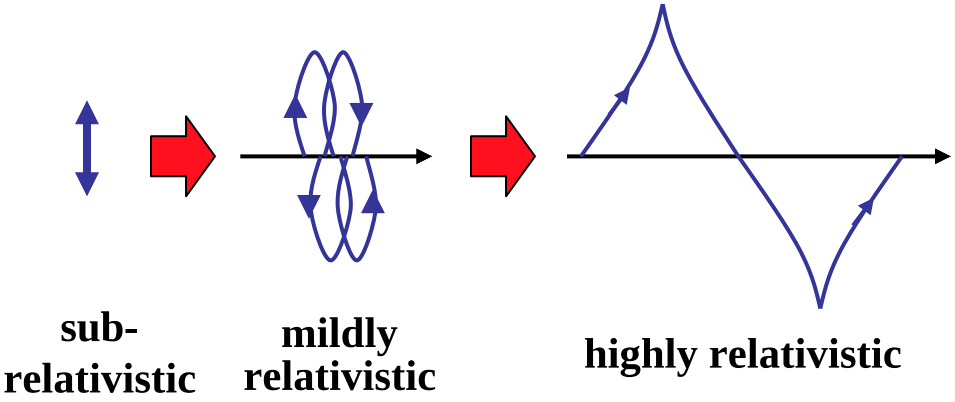
Good idea

Light pressure pushes particles forward



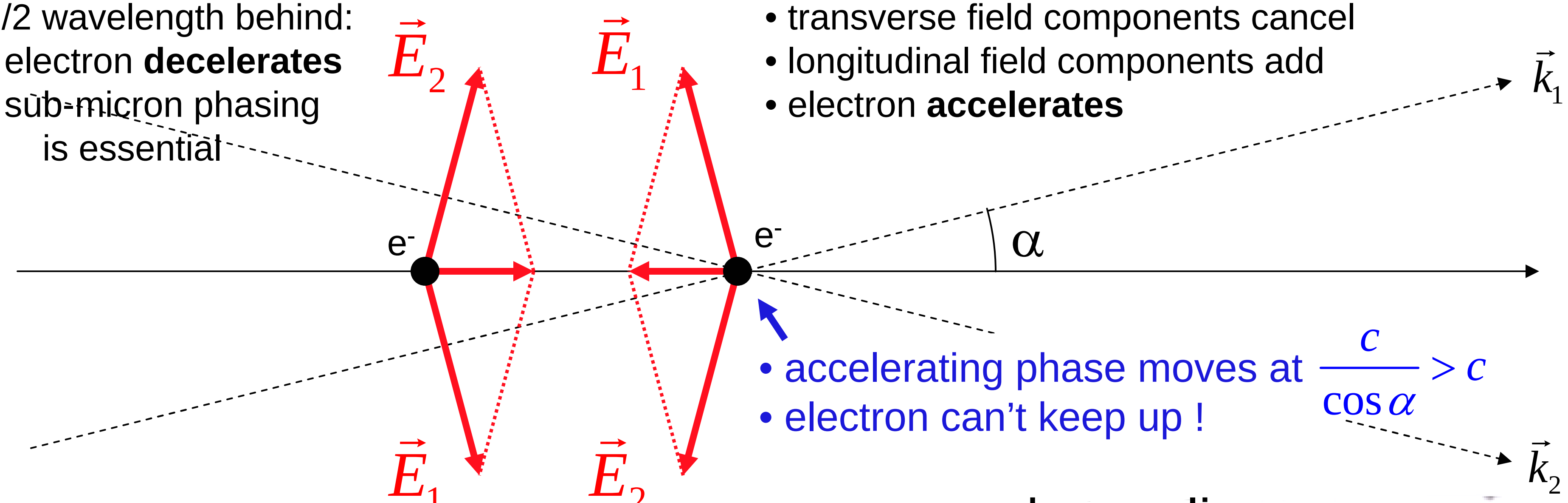
Dumb idea

Electron trajectories become complicated, even chaotic ⇒ poor e^- beam quality



Radiation losses are high

Two laser beams intersecting in vacuum can accelerate an electron longitudinally

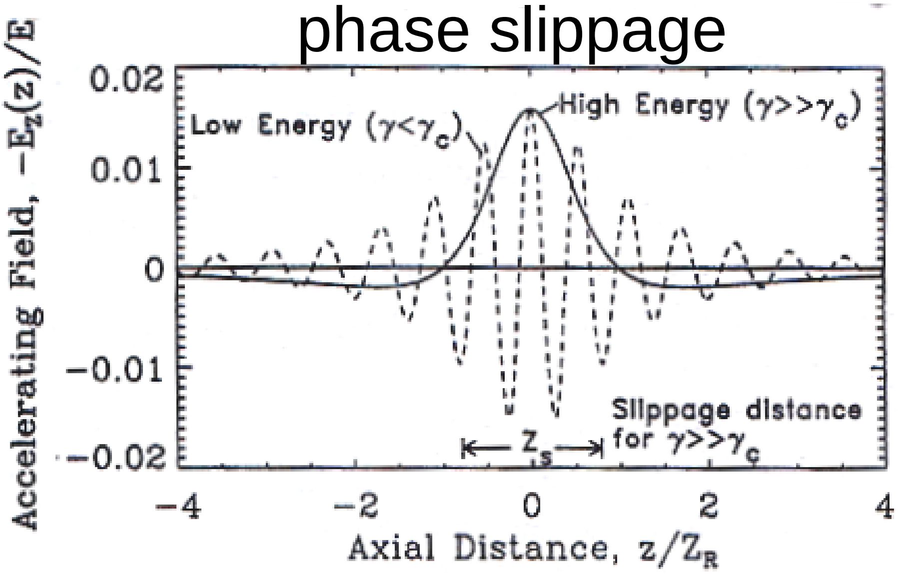


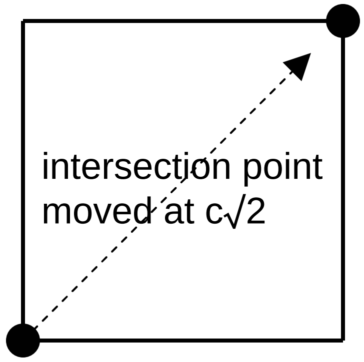
1/2 wavelength behind:
- electron **decelerates**
- sub-micron phasing is essential

- transverse field components cancel
- longitudinal field components add
- electron **accelerates**

- accelerating phase moves at $\dfrac{c}{\cos\alpha} > c$
- electron can't keep up !

phase slippage

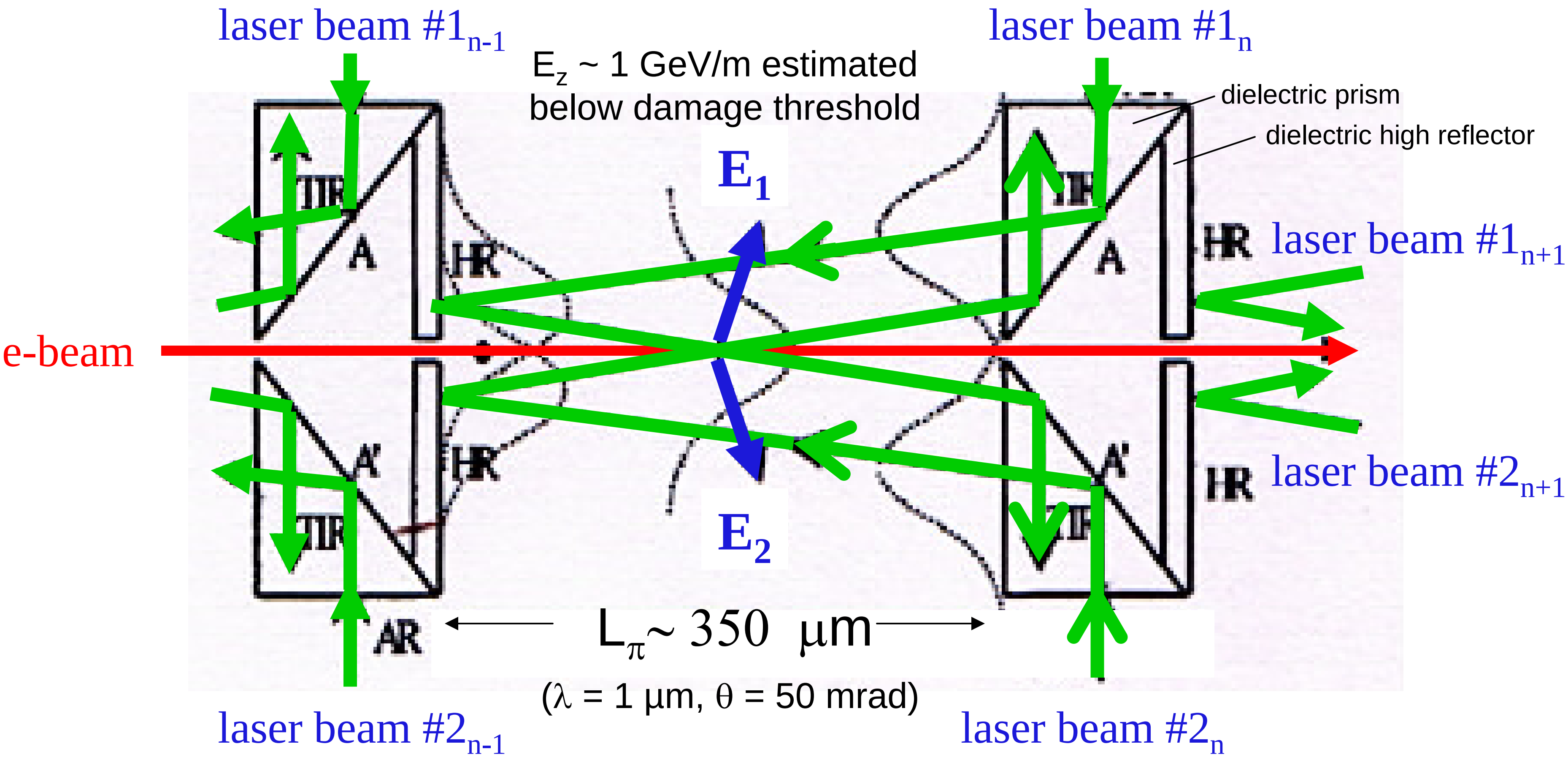




intersection point moved at c√2

Direct Laser Acceleration in vacuum requires microstructured cavities to manage phase slippage

Huang & Byer, “Proposed high-gradient laser-driven electron accelerator using crossed laser focusing,” *Appl. Phys. Lett.* **69**, 2175 (1996)



- E_z << E, low overlap with electron beam ⇒ low efficiency
- Experimental results had to wait 9 years

Laser acceleration in vacuum was first demonstrated in 2005

Plettner, *Phys. Rev. Lett*. **95**, 134801 (2005)

800 nm, 4 ps, 0.5 mJ

30 MeV
2 ps
10 pC

**No acceleration without a boundary,
as per Lawson-Woodward Theorem**

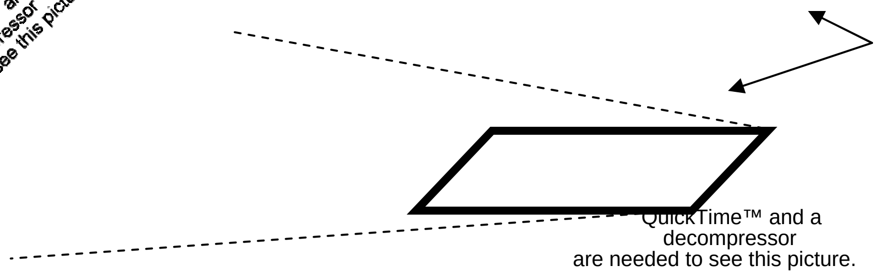
**This is acceleration by
"Inverse Transition Radiation"**

*radiation emitted by a charged particle
on crossing a dieletric boundary*

Side-pumped transparent dielectric grating structure utilizes the transverse laser electric field efficiently

Plettner, “Proposed few-cycle laser-driven particle accelerator structure,” *Phys. Rev. ST-AB* **9**, 111301 (2006)

QuickTime™ and a decompressor are needed to see this picture.



QuickTime™ and a decompressor are needed to see this picture.

few-cycle fs laser pulse with 45° pulse-front tilt

plane wave phase front, stable carrier-envelope phase

Projected performance:
- 1 to 10 GeV/m gradient w/o damage
- 10^6 e^-/bunch with 8% efficiency

QuickTime™ and a decompressor are needed to see this picture.

GRAND VISION: Harness...

... micro-fabrication capabilities of microelectronics industry

... latest fs laser technology

to forge compact particle accelerators of the future

courtesy R. L. Byer

QuickTime™ and a
decompressor
are needed to see this picture.

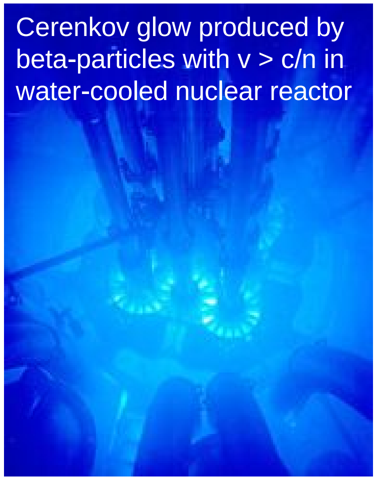
QuickTime™ and a
decompressor
are needed to see this picture.

DLA has been demonstrated with CO_2 lasers

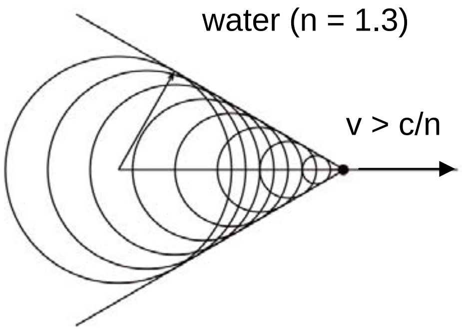
CERENKOV RADIATION:

P. Cerenkov, *Doklady Akad. Nauk. SSSR* **2**, 415 (1934)

(optical shock wave)



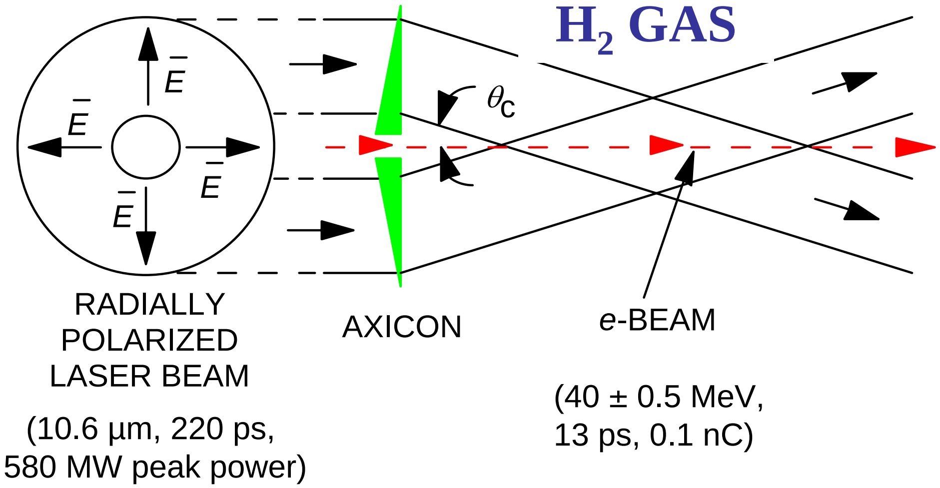
Cerenkov glow produced by beta-particles with v > c/n in water-cooled nuclear reactor



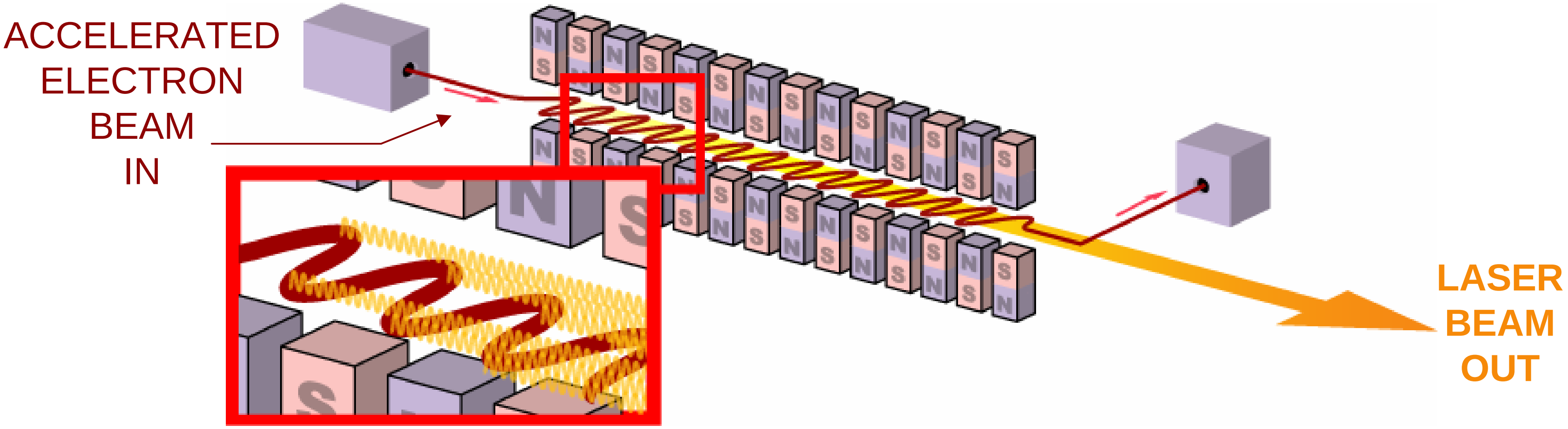
Inverse Cerenkov Accelerator

Kimura *et al*., PRL **74**, 546 (1995); Campbell *et al*., IEEE TPS **28**, 1094 (2000)

- **gas** slows light phase velocity to match electron velocity at Cerenkov angle θ_c
  - 9% energy gain demonstrated (40 → 43.7 MeV)
  - Works best for high γ *e*-beams



FREE ELECTRON LASER:



Inverse Free Electron Laser (IFEL)

van Steenbergen *et al*., PRL **77**, 2690 (1996); Kimura *et al*., Phys. Rev. ST-AB **7**, 009301 (2004)

ACCELERATED

Undulator magnet array phase-matches e-beam with copropagating laser beam.

OUT

- utilizes transverse component of E field
- ≈5% energy gain demonstrated
- Best for low to moderate γ *e*-beams
- Synchrotron losses problem at high γ

QuickTime™ and a
decompressor
are needed to see this picture.

IN

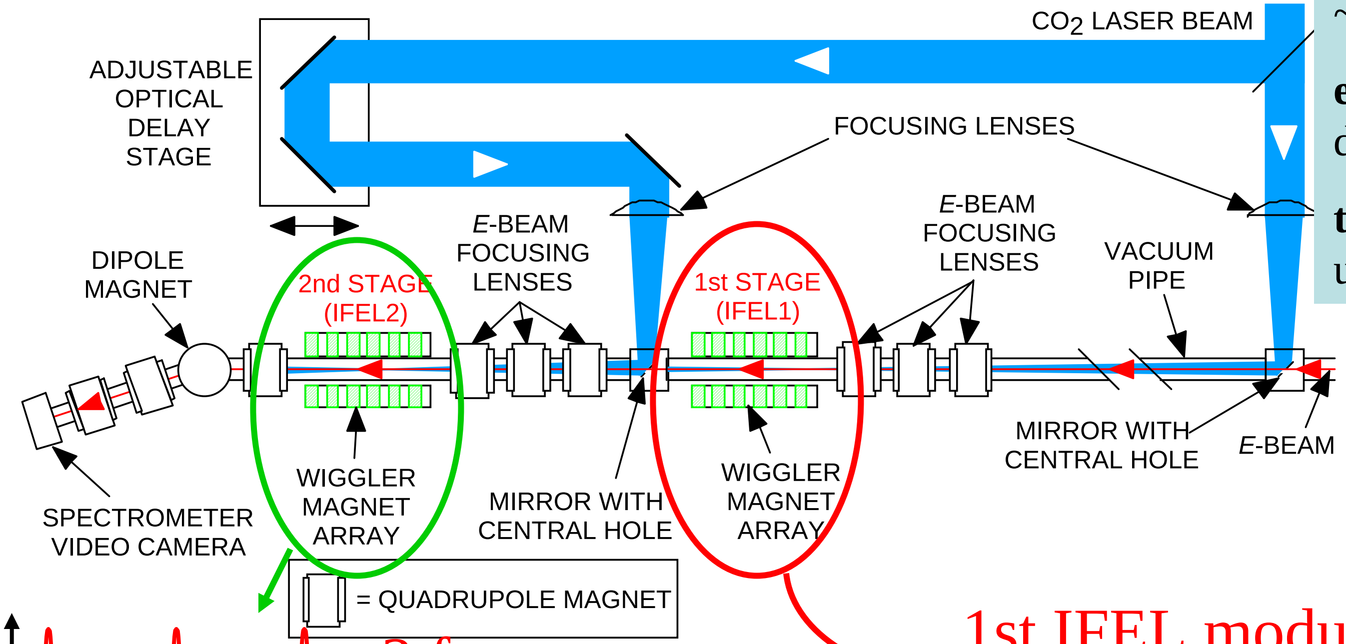
Staged Electron Laser Acceleration (STELLA)

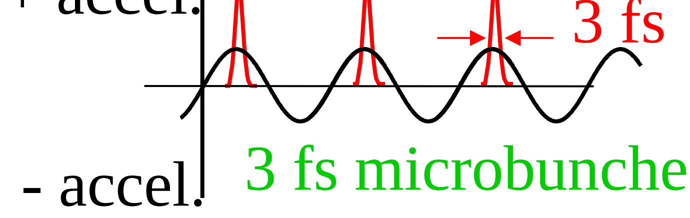
- STELLA demonstrated staged acceleration for the first time
- STELLA used two identical IFELs driven by BNL ATF CO_2 laser

energy shift:
~ 8 MeV

energy spread:
down to 0.36%

trapping efficiency:
up to 80%





1st IFEL modulates e-beam energy (± 0.5%)

3 fs microbunches form at 2nd IFEL, where they are accelerated

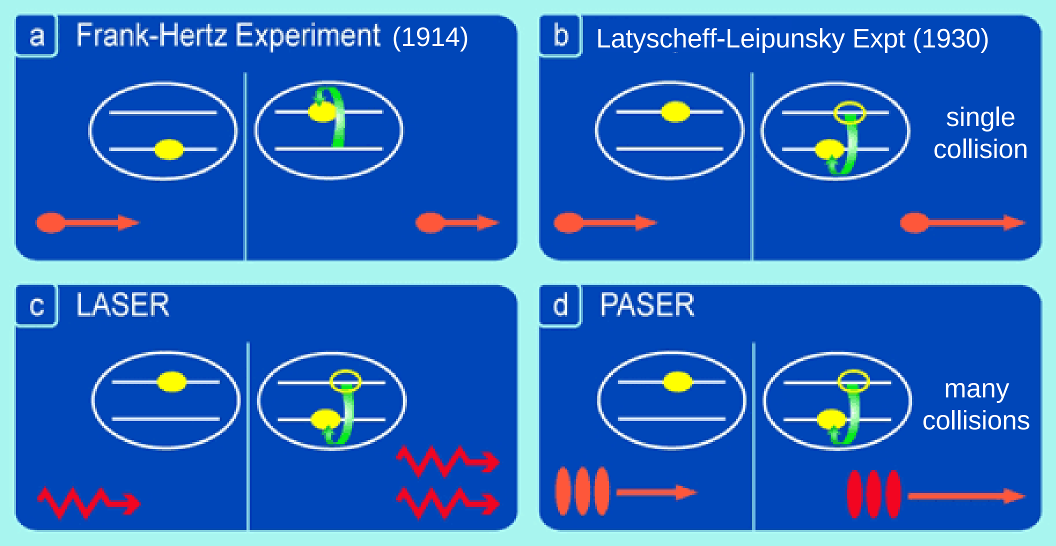
Kimura *et al.*, PRL **86**, 4041 (01)
____________, PRL **92**, 054801 (04)

Technion Institute - Israel

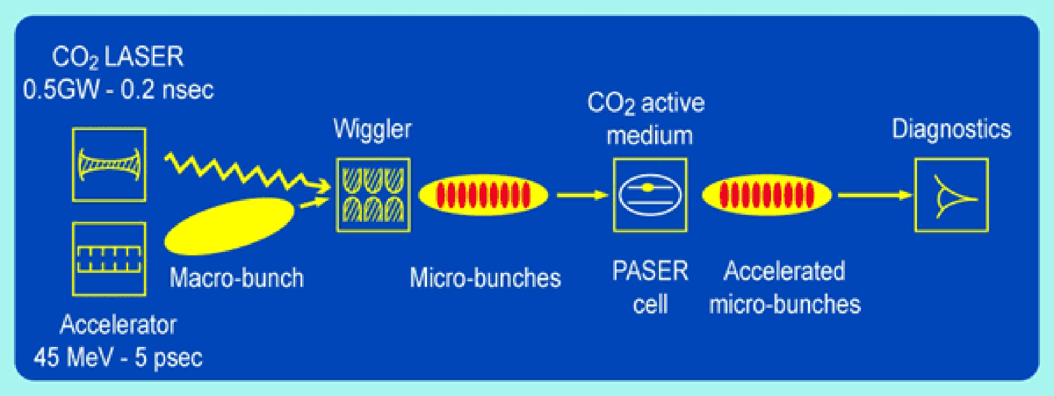
PASER: Particle Acceleration by Stimulated Emission of Radiation

Banna *et al*., *Phys. Rev. Lett*. **97**, 134801 (2006); *Phys. Rev. E* **74**, 046501 (2006)

PASER CONCEPT



EXPERIMENTAL SET-UP



EXPERIMENTAL RESULTS

QuickTime™ and a
decompressor
are needed to see this picture.

~ 2 x 10^6 collisions

Direct laser acceleration can (unintentionally) play a role even in laser-driven "plasma" accelerators

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

*simulation showing relative importance of **Direct Laser Acceleration (DLA)** vs. **Laser Wakefield Acceleration (LWFA).***

SUMMARY: Part I

I) Direct Laser Acceleration of Electrons

- visible lasers: ITR accelerator demonstrated in 2005 (30 → 30.03 MeV)
- CO_2 lasers: ICA, IFEL demonstrated 1995-present (40 → 45 MeV)
- PASER: fundamental new concept demonstrated in 2006 (45 → 45.2 MeV)
- present in some laser-plasma accelerators
- experiments at proof-of-principle stage, but many visionary ideas

II. Radiation from electrons accelerated by lasers & conventional linacs

Linear* Thomson scatter:

light scatter from free electrons

J. J. Thomson, *Conduction of Electricity through Gases* (Cambridge U. Press, 1906).

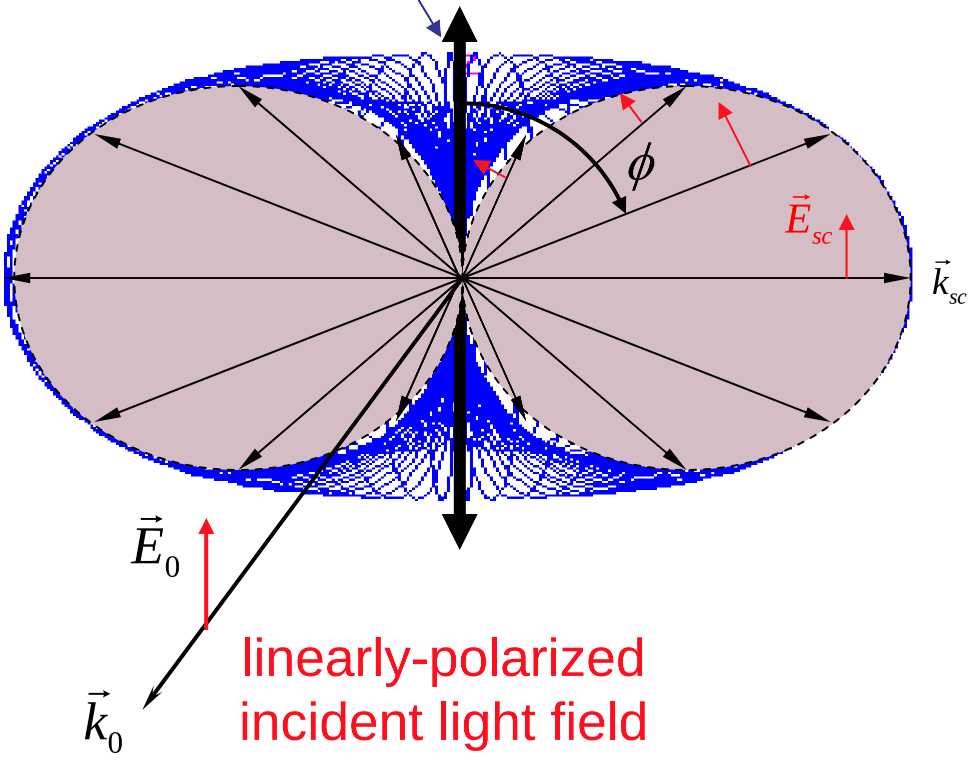
QuickTime™ and a
decompressor
are needed to see this picture.

e$^-$ motion in incident field:

$$\frac{d\vec{v}}{dt} = \frac{e}{m}\vec{E}_0 e^{ikz-i\omega t}$$

*Neglecting **v** × **B** force, relativistic e$^-$ mass increase, and Compton recoil

J. J. Thomson
1856-1940



linearly-polarized
incident light field

Properties of 90º Thomson scatter

$$\vec{E}_{sc} = \vec{E}_0 \sin\phi$$

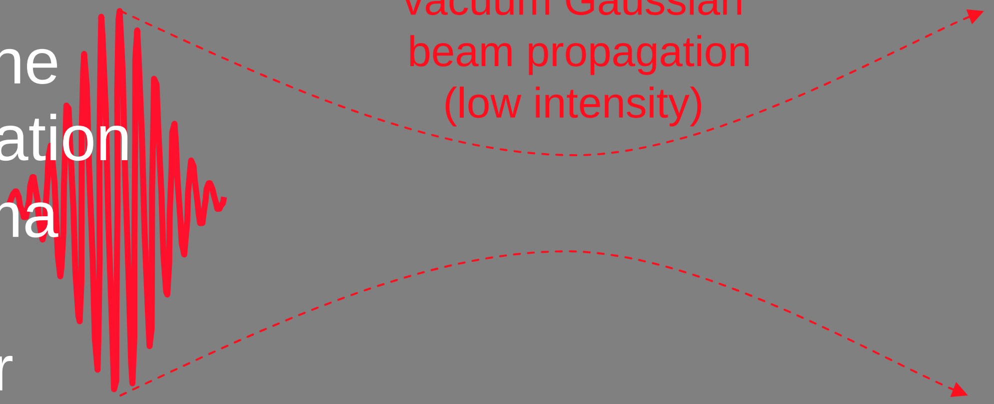
$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{mc^2}\right)^2 \sin^2\phi$$

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 0.665\times10^{-24}\ \mathrm{cm}^2$$

J. D. Jackson, *Classical Electrodynamics, 3rd ed., Sec. 14.1*

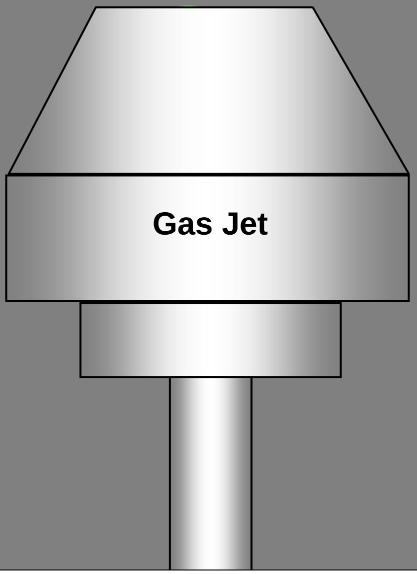
Intense Laser Pulse Propagation through Ionized Gas Jet

We can observe the laser pulse’s propagation path thru the plasma by imaging 90° Thomson scatter



Gas Jet Fires

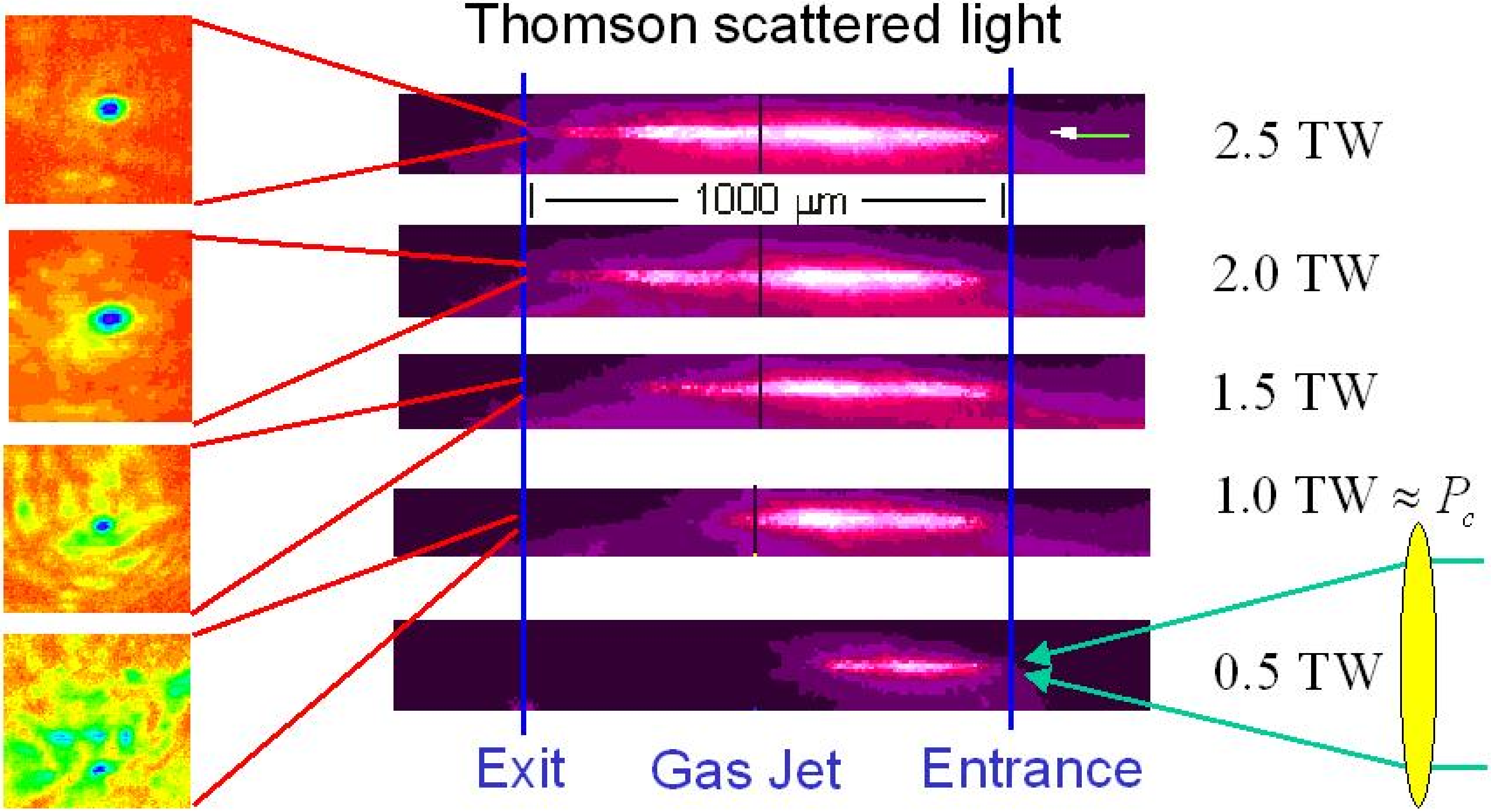
Laser Pulse Focuses, Ionizes Gas, and Scatters from free e^-



Relativistic self-guiding of intense laser pulse measured by linear Thomson side scatter

Axial-imaging

Side-imaging of Thomson scattered light

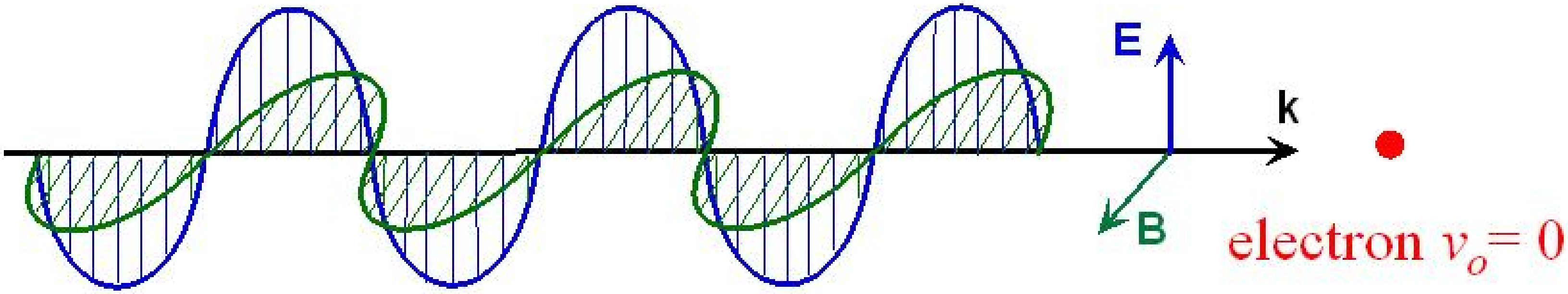


R. Wagner, S.-Y. Chen, A. Maksimchuk and D. Umstadter, PRL **78**, 3125 (1997).

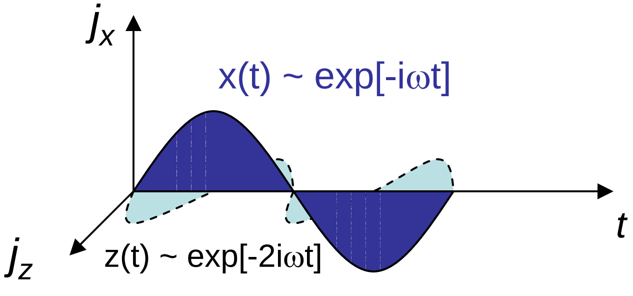
courtesy Don Umstadter

Nonlinear Thomson Scatter

Sarachik & Schappert, *Phys. Rev. D* **1**, 2738 (1970).



$$\mathbf{k}=k\hat{\mathbf{z}},\quad \mathbf{E}=E_0\cos(kz-\omega t)\hat{\mathbf{x}},\quad \mathbf{B}=B_0\cos(kz-\omega t)\hat{\mathbf{y}}$$

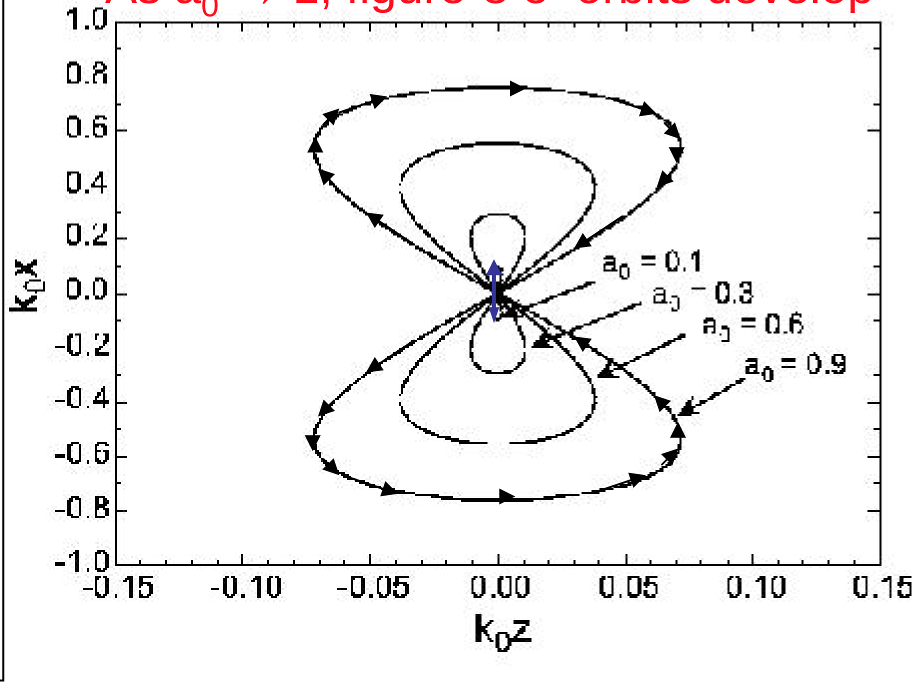


As a_0 increases, harmonics radiate:

$$\vec{J}(t)=\sum_n \vec{j}_n(a_0)e^{-in\omega t}$$

each with its own intensity-dependent radiation pattern

As $a_0 \rightarrow 1$, figure-8 e^--orbits develop



As a_0 increases, harmonics radiate in intensity-dependent angular patterns

n = 1 thru 10 **electron motion** **laser field**

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

n = 1 **n = 2** **n = 3**

courtesy Don Umstadter

Experimental Confirmation

17 December 1998

International weekly journal of science

nature

www.nature.com

Relativistic Thomson scattering

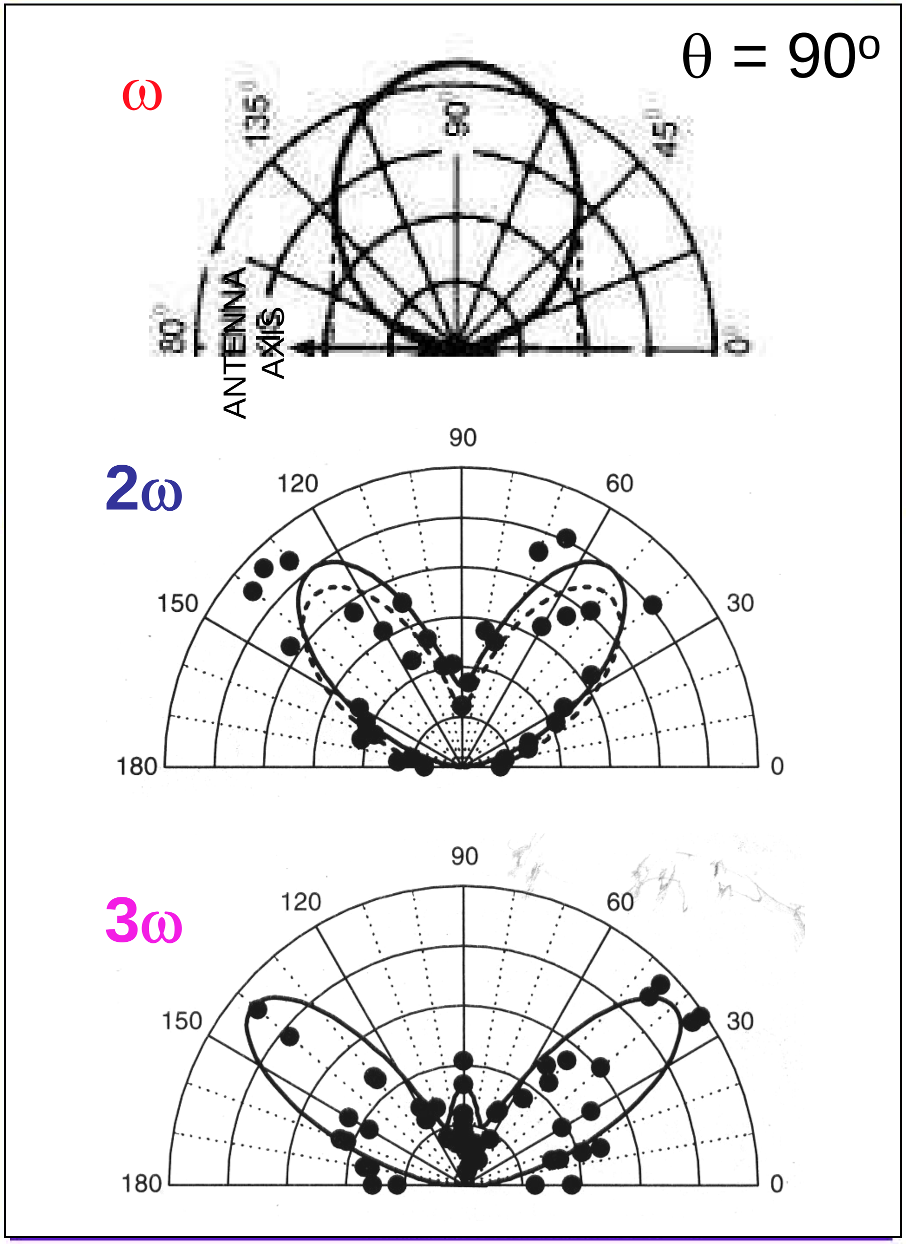
HIV treatment
Changes in thymic function

Polysaccharide elasticity
Stretching the rings

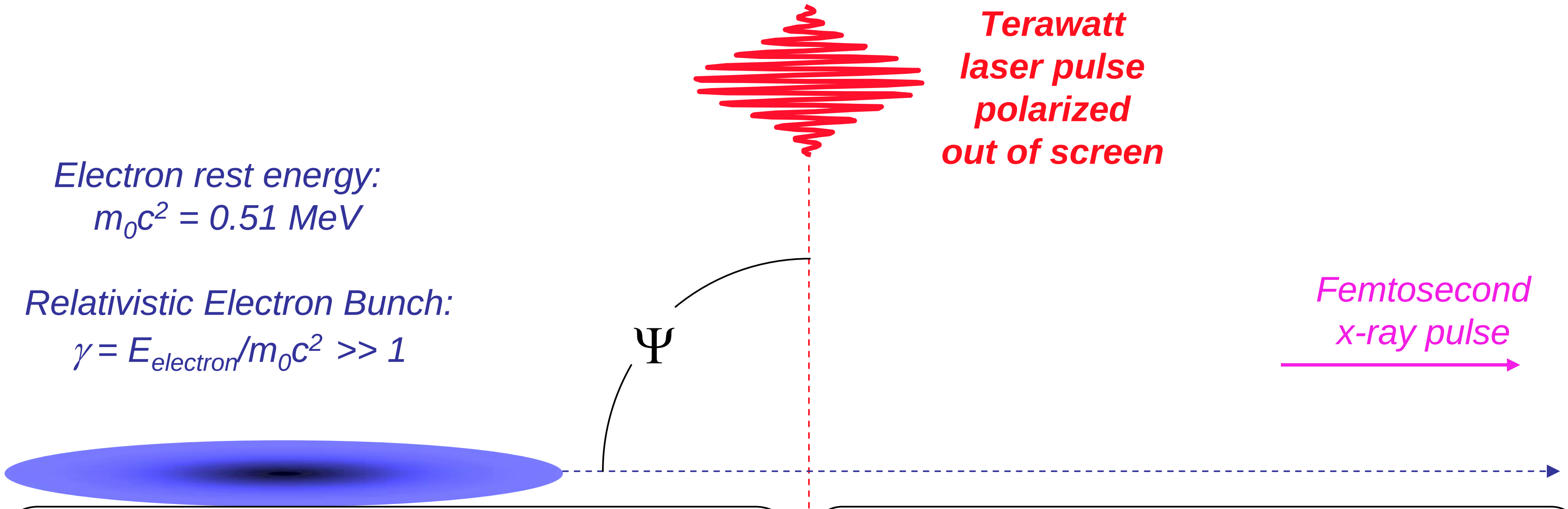
Genetic instability

Nonlinear Thomson scatter provides direct experimental evidence for nonlinear electron orbits that underlie high-field laser-plasma interactions.

S. Chen, A. Maksimchuk and D. Umstadter, *Nature*, **396**, 653 (1998).
S. Chen *et al.*, " *PRL*, **84**, 5528 (2000).



Linear Thomson scatter from linearly accelerated relativistic electrons



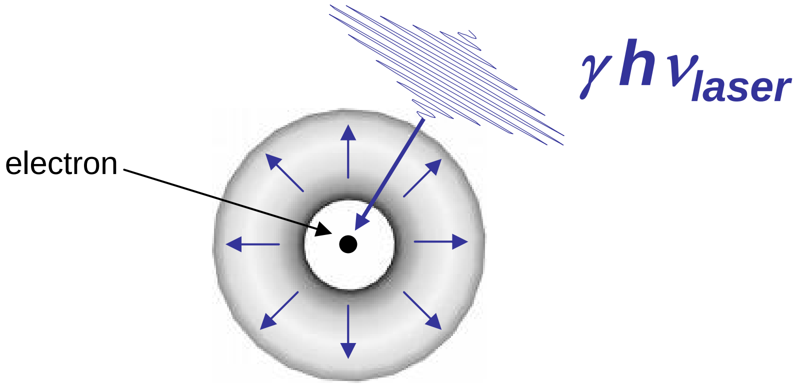
Terawatt
laser pulse
polarized
out of screen

Electron rest energy:
$m_0c^2 = 0.51$ *MeV*

Relativistic Electron Bunch:
$\gamma = E_{electron}/m_0c^2 >> 1$

Femtosecond
x-ray pulse

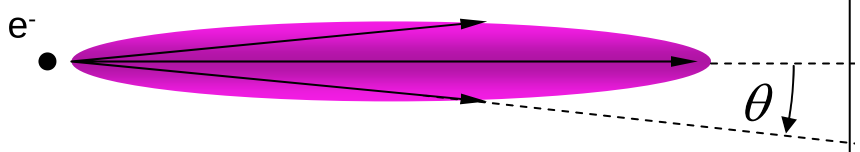
Lorentz transform to e^- rest frame



Thomson-scattered
dipole radiation at $\gamma h\nu_{laser}$

Lorentz transform back to lab frame

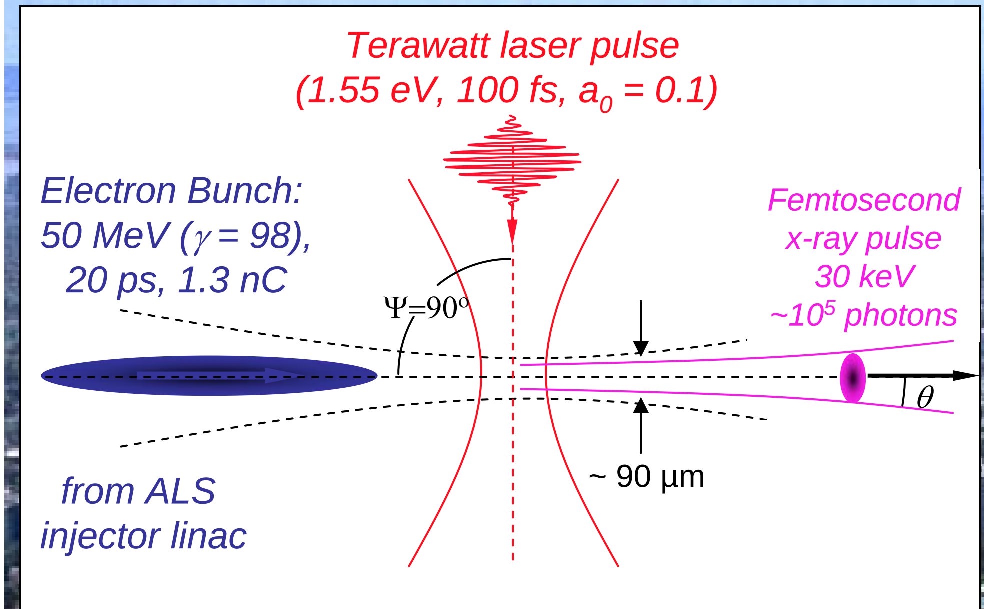
Thomson-scatter
photon energy: $h\nu_x = 2\gamma^2(h\nu_{laser})\dfrac{1-\cos\Psi}{1+\gamma^2\theta^2}$



- strongly forward peaked for $\gamma >> 1$
- $h\nu_x/h\nu_{laser} \sim 2\gamma^2$ (visible → x-ray)

The pioneering experiment was performed at LBNL

R. W. Schoenlein *et al*., “Femtosecond X-ray pulses at 0.4 Å generated by 90º Thomson scatter: A Tool for Probing the Structural Dynamics of Materials,” *Science* **274**, 236 (1996).

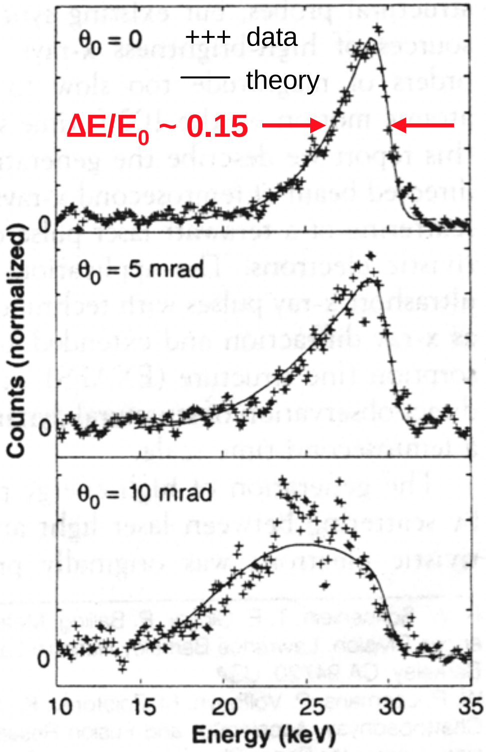


- 90º geometry was chosen to minimize x-ray pulse duration, at the expense of conversion efficiency

Measured Profile:

CCD image of phosphor screen that is sensitive to 10-50 keV x-rays.

QuickTime™ and a decompressor are needed to see this picture.

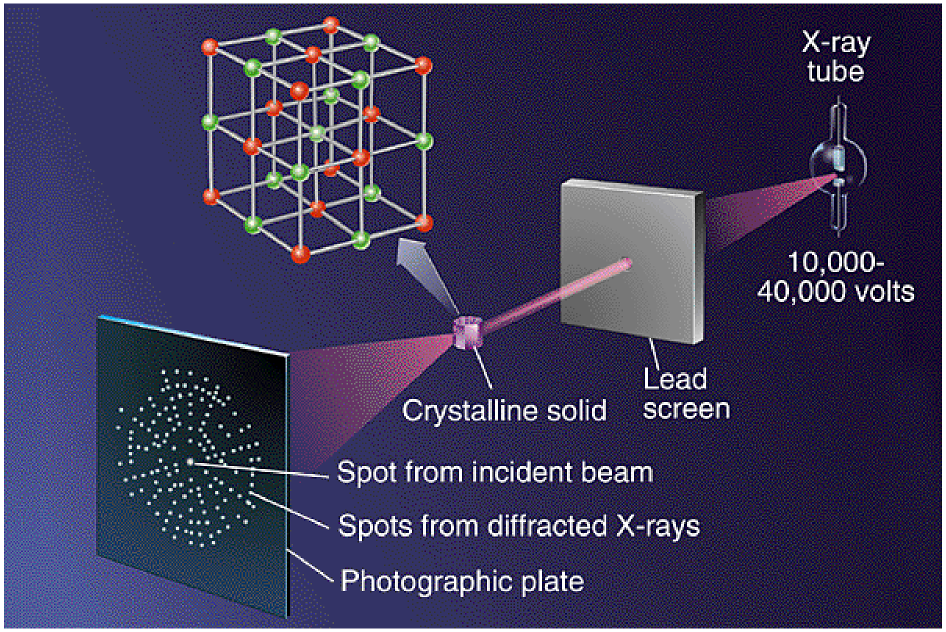


Measured with LN_2-cooled Ge photon-counting detector, using pulse-height analysis.

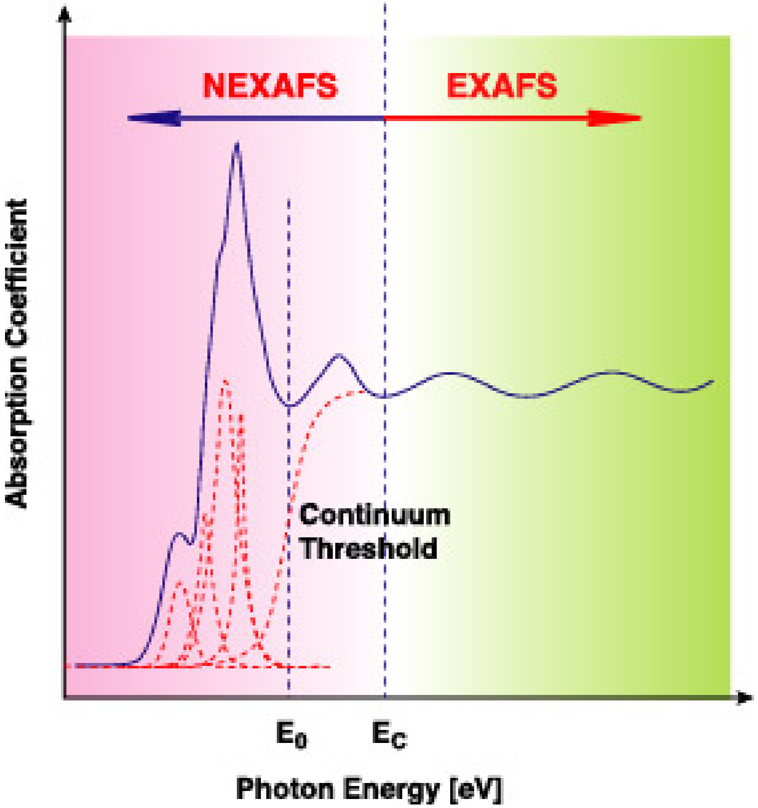
QuickTime™ and a decompressor are needed to see this picture.

Much of condensed matter science is based on x-ray measurements

X-ray Diffraction



X-Ray Absorption with Strong NEXAFS Features and Weak EXAFS Oscillations



The past decade has seen the birth of “fs x-ray science”

Fs X-ray pulses shorter than a molecular vibrational period can probe ultrafast structural dynamics of materials

Pfeifer et al., “Femtosecond x-ray science,” *Rep. Prog. Phys*. **69**, 443 (2006).

optical pump/x-ray-probe experiment

QuickTime™ and a
decompressor
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x-ray absorption in VO_2

Cavalleri *et al*., *Phys. Rev. Lett*. **95**, 067405 (2005)

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x-ray diffraction from melting InSb

Lindenberg, *Science* **308**, 392 (2005)

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x-ray diffraction showing lattice vibrations in bismuth

Sokolowski-Tinten *et al*., *Nature* 422, 287 (2003)

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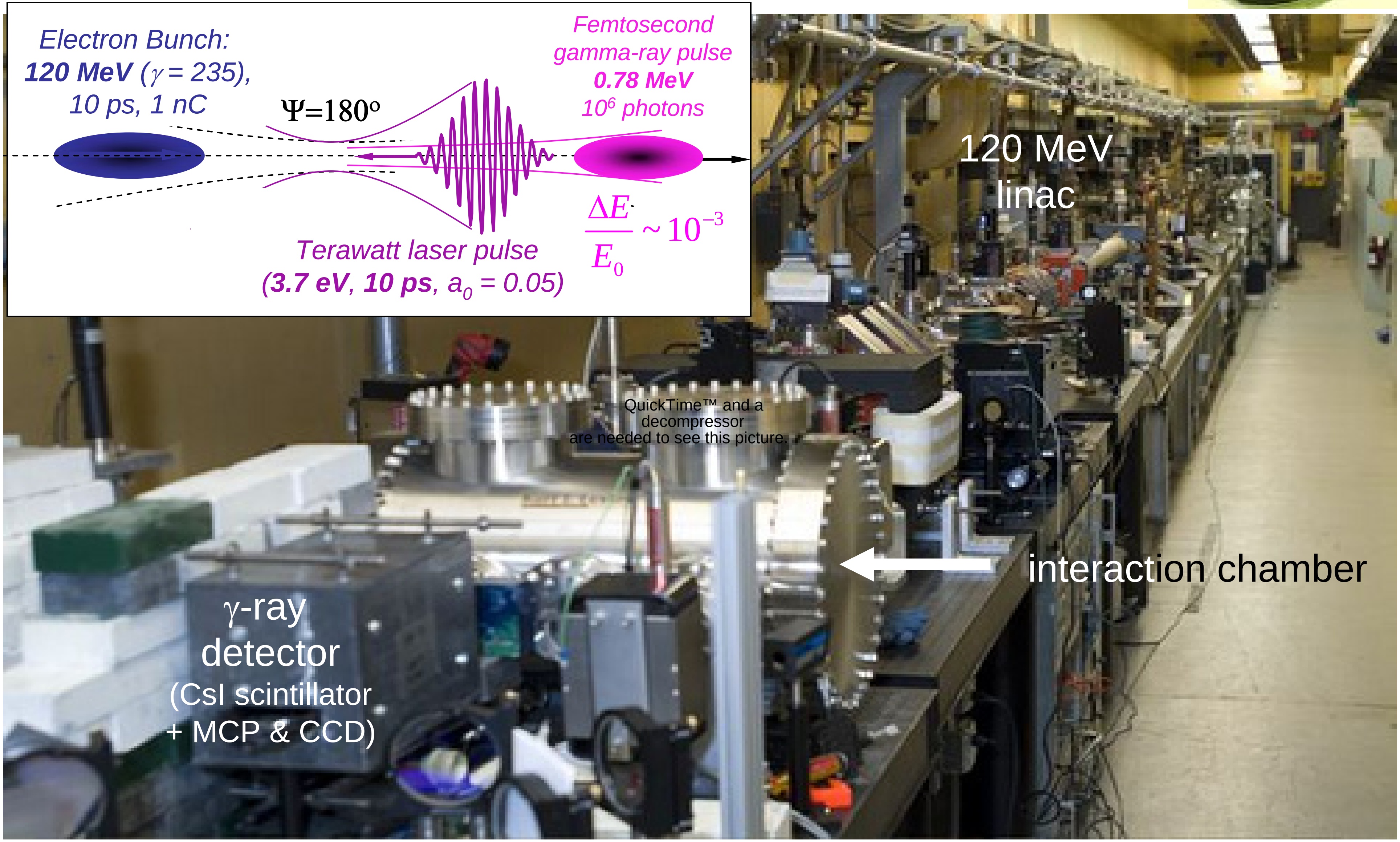
Researchers at Lawrence Livermore have developed T-REX (Thomson-Radiated Extreme X-rays) a bright 0.78 MeV gamma-ray source

CPF Barty, CLEO postdeadline paper (2008); Gibson, *Phys. Plasmas* **11**, 2857 (2004)



0.78 MeV gamma-rays from T-REX

CsI scintillator + micro-channel plate + CCD

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courtesy Craig Siders

Compton light sources could become the brightest γ-ray (hν > 100 keV) sources known to science

Hartemann, “High-energy scaling of Compton scattering light sources,” *Phys. Rev. ST-AB* **8**, 100702 (2005)

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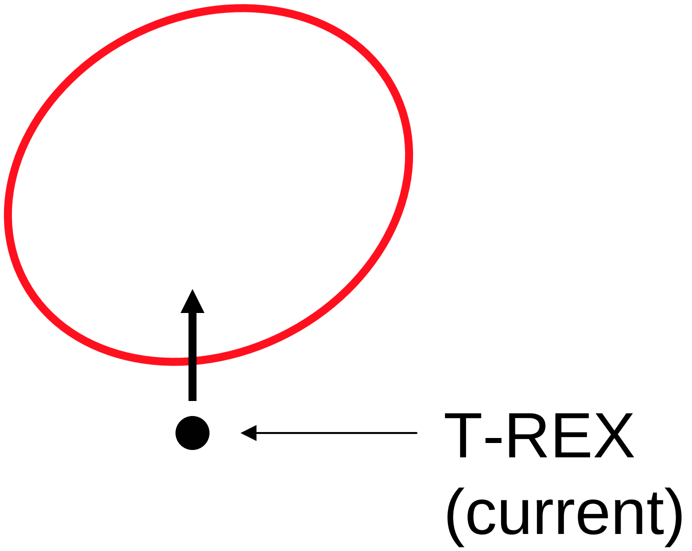
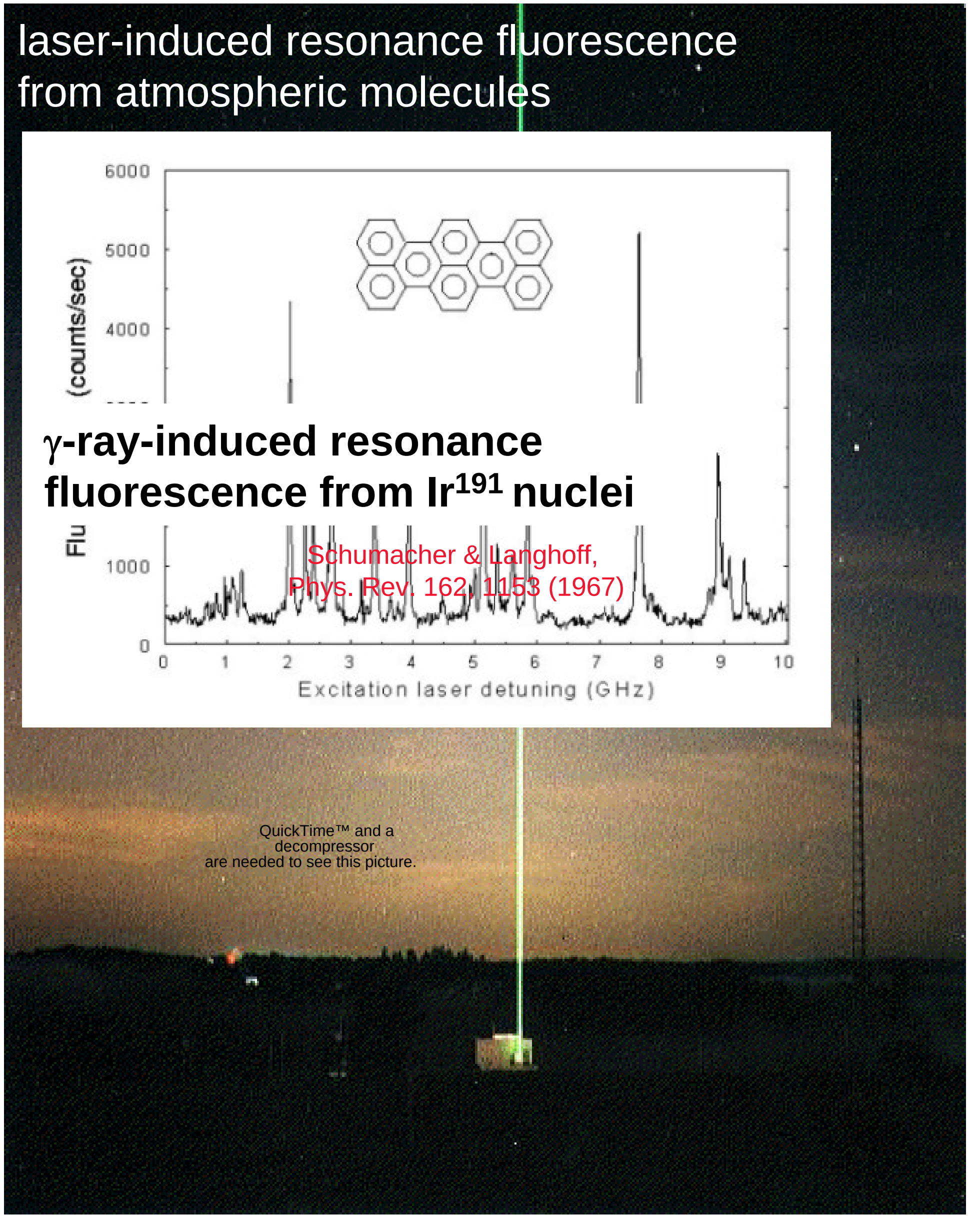


Nuclear resonance fluorescence spectroscopy & isotope-specific imaging



laser-induced resonance fluorescence from atmospheric molecules

γ-ray-induced resonance fluorescence from Ir^{191} nuclei

Schumacher & Langhoff, Phys. Rev. 162, 1153 (1967)

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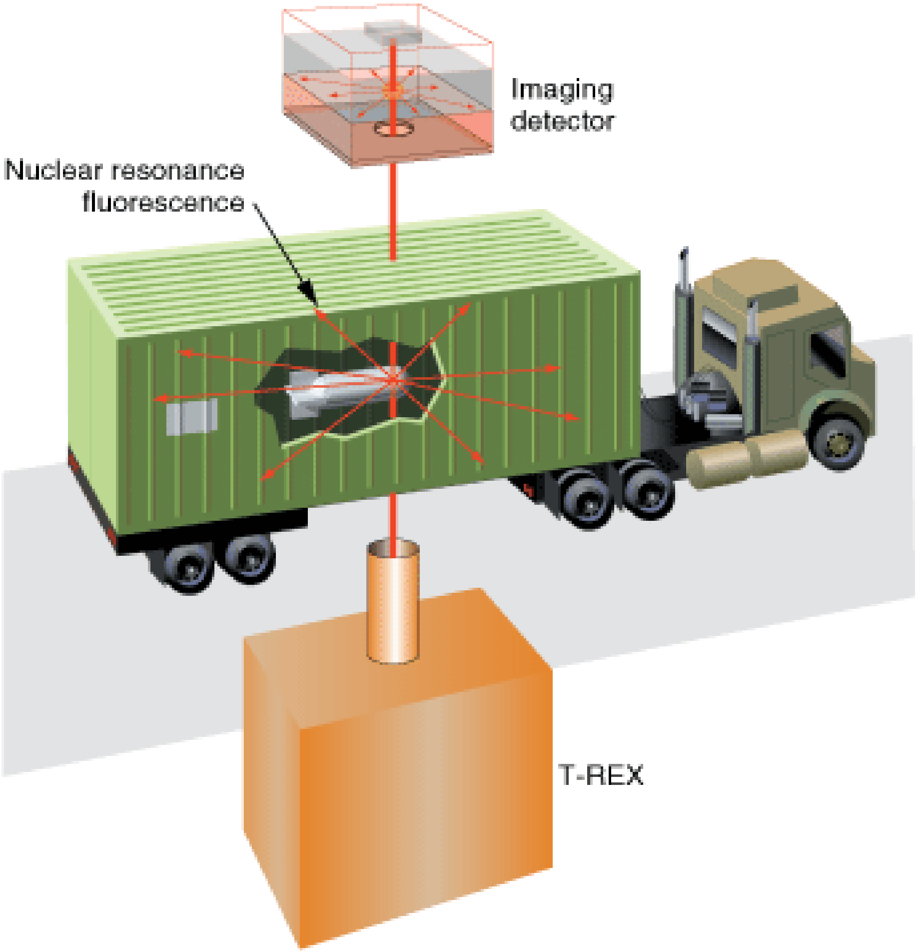

For producing narrow-band x-rays, ultrashort, intense laser pulses are not best

Hartemann *et al*., Phys. Rev. ST-AB **8**, 100702 (2008)

Peak on-axis x-ray brightness
(normalized units)

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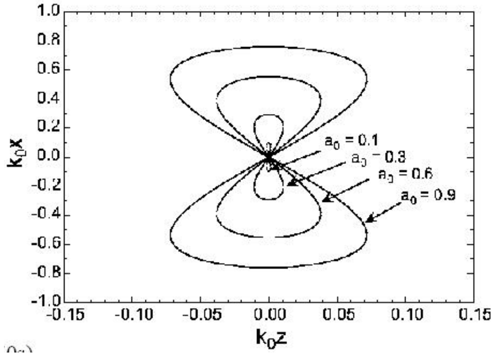
Normalized X-ray Frequency

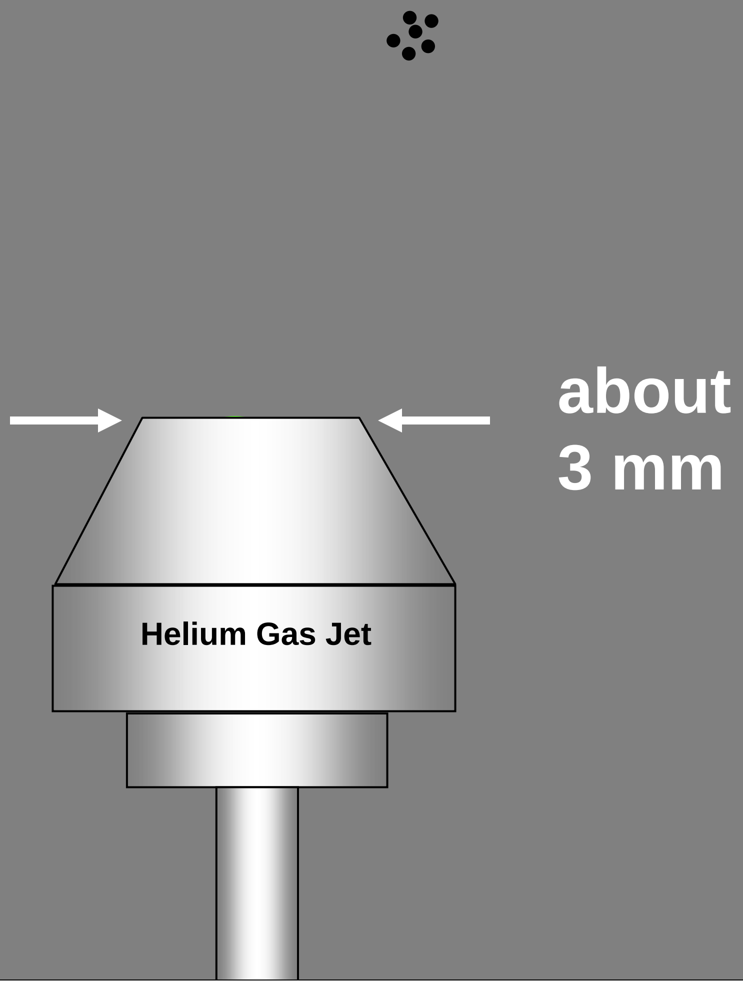
Nonlinear e$^-$ orbits degrade brightness and bandwidth for short, intense pulses



Laser-Plasma Electron Accelerator

Tajima & Dawson, Phys. Rev. Lett. ***43,*** *267 (1979)*

Is this a potential
Thomson x-ray source?



Gas Jet Fires

Laser Pulse Focuses

Ionize Gas & Make Wave

Wave Captures and
Accelerates Electrons

How do laser-plasma accelerators stack up against conventional linacs as Compton x-ray sources?

Hartemann, “High-energy scaling of Compton scattering light sources,” *Phys. Rev. ST-AB* **8**, 100702 (2005)

x-ray brightness
(photons/mm^2 • mrad^2 • s • 0.1% bandwidth)

e- energy

electrons

photons

$$B_x \propto \frac{\gamma_0^2 N_e N_\lambda}{\varepsilon^2 \Delta\tau} \qquad \textit{for } \theta = 180^o$$

e- beam transverse emittance

e- bunch duration

	laser-plasma accelerator	conventional “small” LINAC
length:	**~ 1 cm**	10 to 100 m
γ_0:	100 to 1000	100 to 1000
N_e:	~ 0.1 nC	~ 1 nC
ε:	~ π mm-mrad	~ π mm-mrad
$\Delta\tau$:	**~ 10 fs***	1 to 10 ps

*est. from simulations: Pukhov, *Appl. Phys. B* **74**, 355 (2002)

Table-top Thomson backscatter from laser-accelerated electrons

Schwoerer *et al*., *Phys. Rev. Lett.* **96**, 014802 (2006)

$3\text{x}10^4$ photons/shot

x-ray
spectrum

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are needed to see this picture.

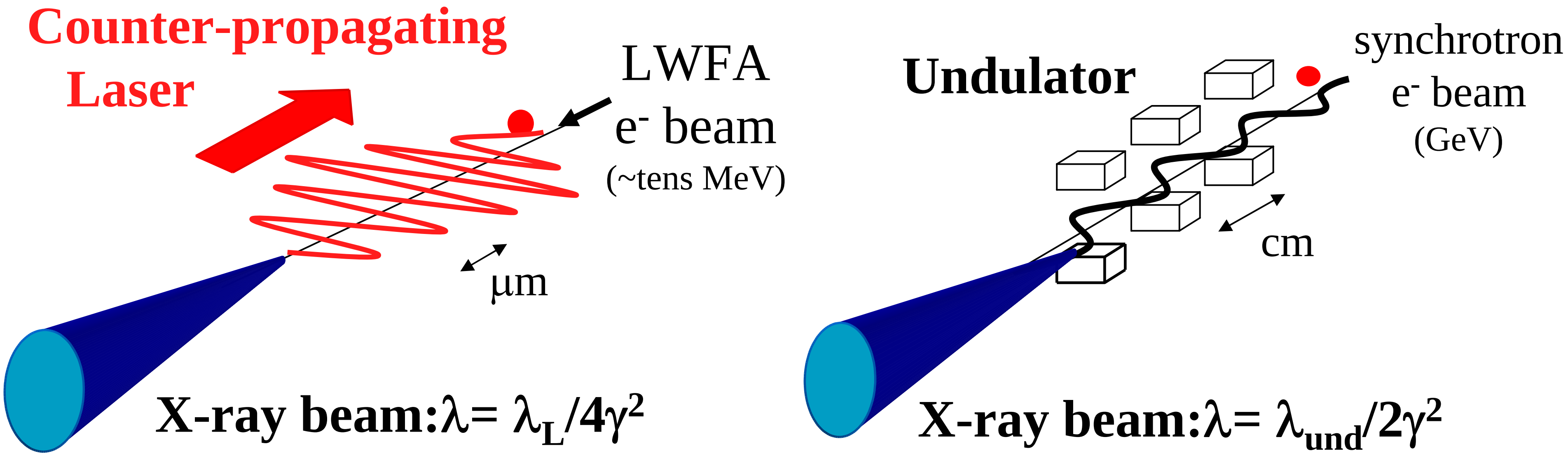
electron
spectrum

Other observations of x-ray radiation from laser-accelerated electrons:

K. Ta Phuoc *et al*., *Phys. Rev. Lett*. **91**, 195001 (2003)

Rousse et al., *Phys. Rev. Lett.* **93**, 135005 (2004)

Counter-propagating laser = short-period undulator



X-ray beam:$\lambda = \lambda_L/4\gamma^2$

X-ray beam:$\lambda = \lambda_{und}/2\gamma^2$

- higher efficiency
- narrower bandwidth

A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator

Schlenvoigt *et al*., *Nature Physics* **4**, 130 (2008)

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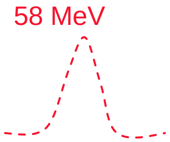
64 MeV



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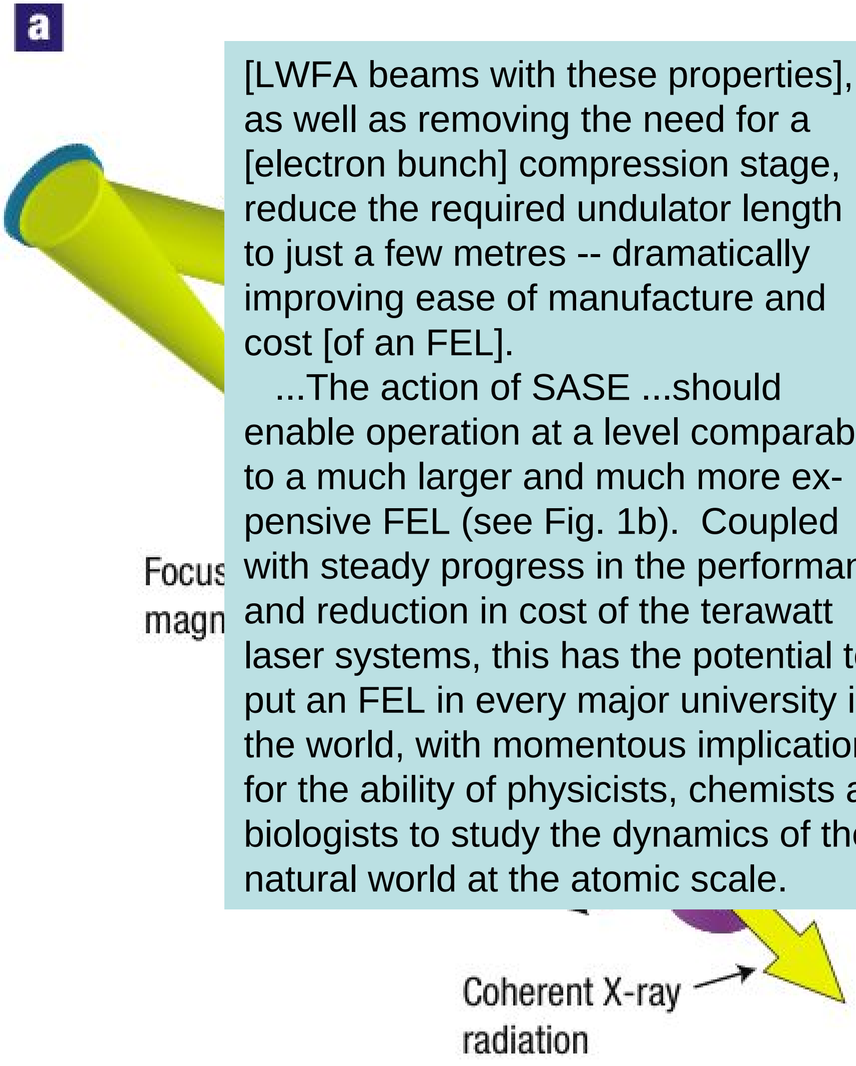
COMPACT X-RAY SOURCES
nature physics | VOL 4 | FEBRUARY 2008

Towards a table-top free-electron laser

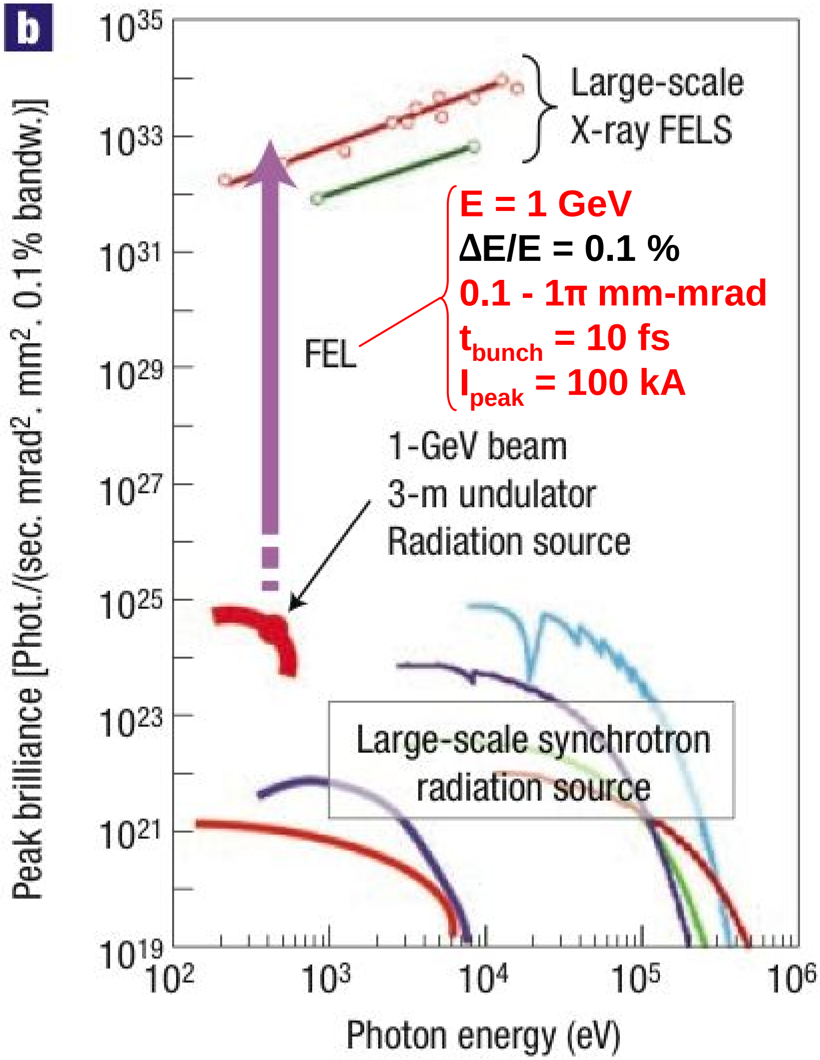
Kazuhisa Nakajima

Synchrotron radiation generated using an electron beam from a laser-driven accelerator opens the possibility of building an X-ray free-electron laser hundreds of times smaller than conventional facilities currently under construction.



[LWFA beams with these properties], as well as removing the need for a [electron bunch] compression stage, reduce the required undulator length to just a few metres -- dramatically improving ease of manufacture and cost [of an FEL].

...The action of SASE ...should enable operation at a level comparable to a much larger and much more expensive FEL (see Fig. 1b). Coupled with steady progress in the performance and reduction in cost of the terawatt laser systems, this has the potential to put an FEL in every major university in the world, with momentous implications for the ability of physicists, chemists and biologists to study the dynamics of the natural world at the atomic scale.



E = 1 GeV
ΔE/E = 0.1 %
0.1 - 1π mm-mrad
t_{bunch} = 10 fs
I_{peak} = 100 kA

SUMMARY

II) Radiation from Laser-Driven Electrons

- linear Thomson scatter from stationary electrons: characterizes intense laser propagation in a plasma
- nonlinear Thomson scatter: characterizes figure-8 electron orbits (1998)
- linear Thomson scatter from relativistic electron bunches
  - side-scatter (LBNL, 1996): helped open up fs x-ray science
  - back-scatter: 1) from 200 MeV linac → bright 0.78 MeV γ-rays (T-REX, 2008)
    2) from poly-energetic LWFA beam → broadband keV x-rays (2006) **
- undulator radiation (near IR) from mono-energetic (~60 MeV) LWFA beam**

**promise of future table-top synchrotrons & FELS when scaled to mono-energetic GeV electron beams from laser-plasma accelerators

Optimizing brightness of Thomson-scattered x-rays is a 13-parameter problem

Hartemann, “High-energy scaling of Compton scattering light sources,” *Phys. Rev. ST-AB* **8**, 100702 (2005)

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e- energy

electrons

photons

$$B_x \propto \frac{\gamma_0^2 N_e N_\lambda}{\varepsilon^2 \Delta\tau} \quad \textit{for } \theta = 180^o$$

e- beam transverse
emittance

e- bunch duration

Even the theoretical optimization problem remains incompletely solved