Perspectives of laser acceleration of particles

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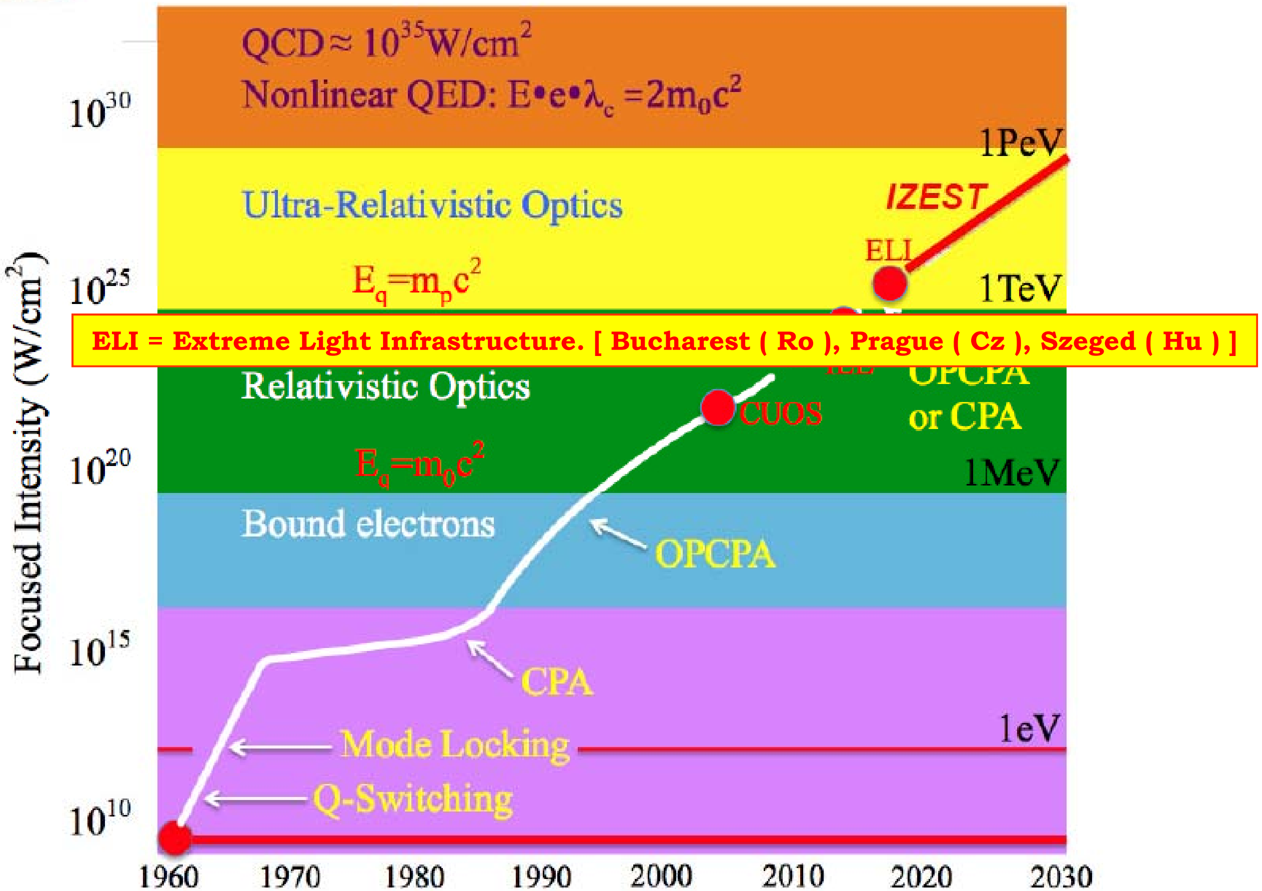
Zimányi School. 07. December 2012.

Large electric field strengths

$$[F_0 /(V / cm)] = 27.46 \times [I_0 /(W / cm^2)]^{1/2}$$

Laser Intensity vs. Years



Taken from T. Tajima's presentation at 'IZEST' [INTERNATIONAL ZETA-EXAWATT SCIENCE AND TECHNOLOGY.] Launching Workshop, Ecole Polytechnique, 28-29 November, 2011. Paris, France.

D. Strickland and G. Mourou [1985]: ‘Chirped Pulse Amplification’ , ‘CPA’

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

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Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The echo is compressed to its original pulse shape by a negatively dispersive delay line [1].

pulse would be free from gain saturation effects, because the frequency varies along the pulsewidth and each frequency component sees gain independently.

A schematic diagram of the amplifier and compression system is shown in fig. 1. A CW mode-locked, Nd : YAG laser (Spectra-Physics Series 3000) is used to produce 150 ps pulses at an 82 MHz repetition rate. Five watts of average power are coupled into 1.4 km of single-mode non-polarization-preserving optical fiber. The fiber (Corning Experimental SMF/DS^{TM})

D. Strickland and G. Mourou: Compression of amplified chirped optical puses. *Opt. Comm.* 56 (3), 219-221 (1985)# . [*Opt. Comm.* 55 (6), 219-221 (1985) „where inadvertently a wrong figure was printed as fig.1.”]

Fermi [1954]

G. A. Schott [1907]; Synchrotron radiation and 'superradiance'. Loss !

2. *Über die Strahlung von Elektronengruppen;*
von G. A. Schott.

$$A'_\mu(y) = 4\pi e \int d\tau G(y - x(\tau)) u_\mu(\tau)$$

§ 1. *Umformung der Lorentzschen Potentiale.* Wir gehen von den bekannten Lorentzschen Potentialen φ und $\mathfrak{a}$ aus, wo

$$(1) \qquad \varphi = \iiint [\varrho] \frac{dx'\,dy'\,dz'}{R}, \quad \mathfrak{a} = \iiint \left[\varrho \frac{\mathfrak{v}}{c}\right] \frac{dx'\,dy'\,dz'}{R}.$$

Hier ist (x, y, z) der Aufpunkt, $dx'\ dy'\ dz'$ ein im Punkte (x', y', z') gelegenes festes Volumelement,

$$R = +\sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2},$$

und ϱ die Ladungsdichte, $\mathfrak{v}$ die Ladungsgeschwindigkeit im Punkte (x', y', z') zur Zeit $t - R/c$. Es sind also ϱ, $\mathfrak{v}$ implizite Funktionen von t, x, y, z; wir wollen nun die Ausdrücke (1) umformen, so daß t als explizite Variable erscheint.

G. A. Schott, Über die Strahlung von Elektronengruppen. *Annalen der Physik* (4) 635-660 (1907)

Synchrotron radiation. 'Search light'. Radiation loss, reaction.

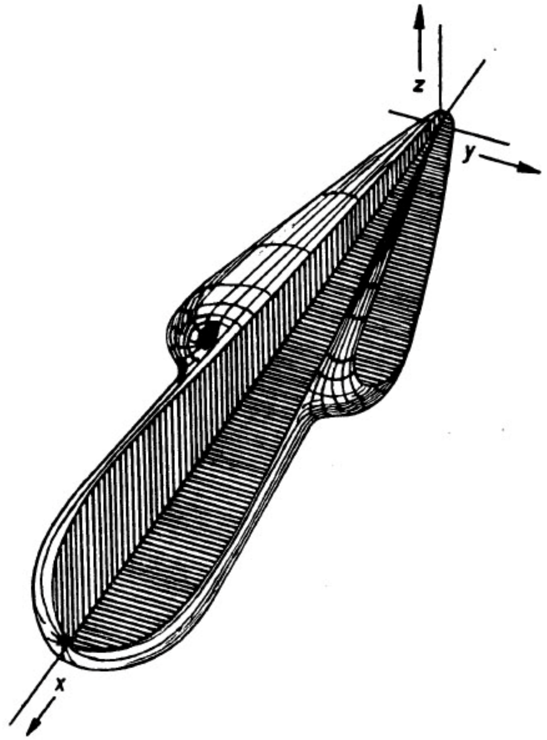


Fig. 1.7. Instantaneous intensity distribution $\Psi_0(\alpha, \gamma)$ of the synchrotron radiation

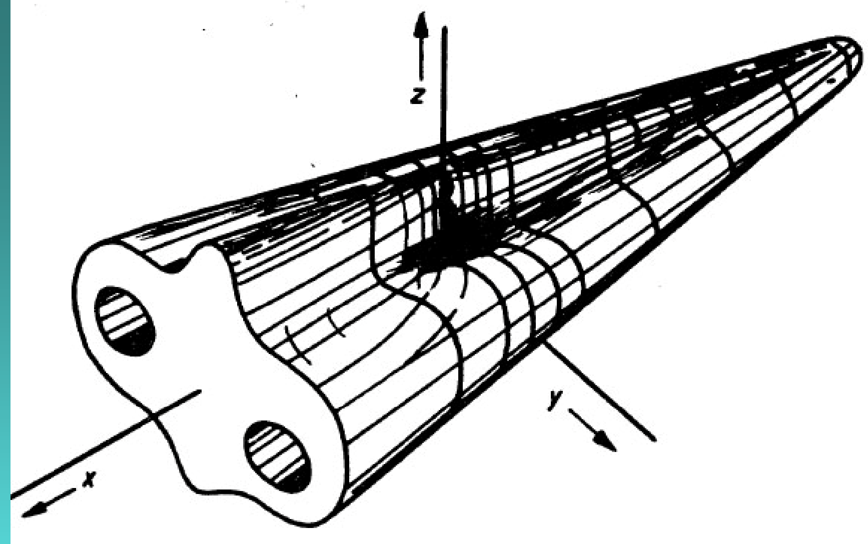


Fig. 1.8. Instantaneous distribution of the σ-component of the synchrotron radiation

In the section the relative minima are to be seen; the small components of the radiation opposite to the motion are shown with enlarged scale

Figures taken from: A. I. Sokolov and I. I. Ternov, Synchrotron radiation. (Springer, Berlin, 1966).

$$\dot{u}^{\mu} = \frac{e}{mc} F^{\mu\nu} u_{\nu} + r_0 \left\{ \frac{e}{mc} \dot{F}^{\mu\nu} u_{\nu} + \frac{e^2}{m^2 c^2} F^{\mu\lambda} F_{\lambda}^{\nu} u_{\nu} - \frac{e^2}{m^2 c^4} u_{\lambda} F^{\lambda\nu} F_{\nu}^{\alpha} u_{\alpha} u^{\nu} \right\}$$

The Importance of Radiation Loss.

Linear : P_{loss} ~ practically zero (however, very costly). Ring: $P_{loss} \sim (E/Mc^2)^4$

Taken from A. Caldwell's presentation „Novel accelerators..." at 'IZEST' [INTERNATIONAL ZETA-EXAWATT SCIENCE AND TECHNOLOGY. Launching Workshop, Ecole Polytechnique, 28-29 November, 2011. Paris, France.]

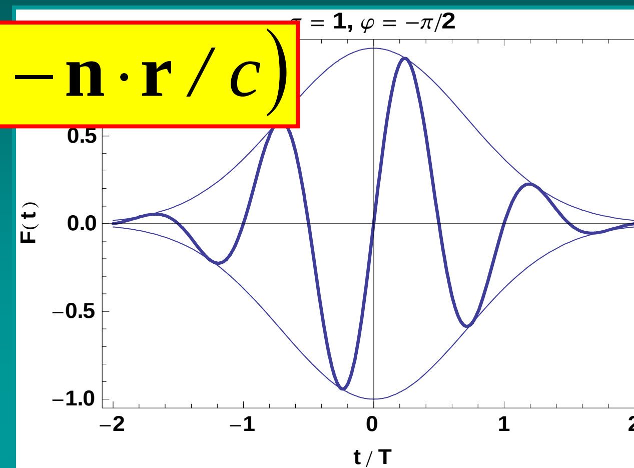
‘Laser field’. Plane wave. ‘Nonrelativistic, relativistic intensities’

$$\mathbf{E}(\mathbf{r},t) = \mathbf{e}F_0 \sin(\omega t - \mathbf{k}\cdot\mathbf{r} + \varphi_0)$$

$$f\left(t - \mathbf{n}\cdot\mathbf{r}/c\right)$$

$$\mathbf{B}(\mathbf{r},t) = \mathbf{n}\times\mathbf{e}F_0 \sin(\omega t - \mathbf{k}\cdot\mathbf{r} + \varphi_0)$$

$$\omega = c\,|\mathbf{k}|, \qquad \mathbf{e}\perp\mathbf{k}, \qquad \mathbf{n}\equiv\mathbf{k}/|\mathbf{k}|$$



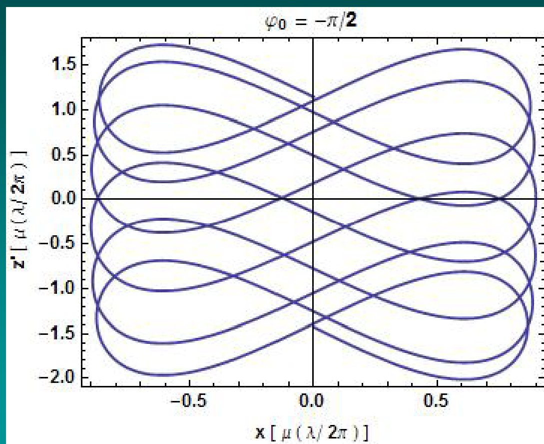
$$\frac{d}{dt}\left[\frac{m_0 d\mathbf{r}(t)/dt}{\sqrt{1-[d\mathbf{r}(t)/dt]^2/c^2}}\right] = -e\mathbf{E}(\mathbf{r}(t),t) - \frac{e}{c}\frac{d\mathbf{r}(t)}{dt}\times\mathbf{B}(\mathbf{r}(t),t)$$

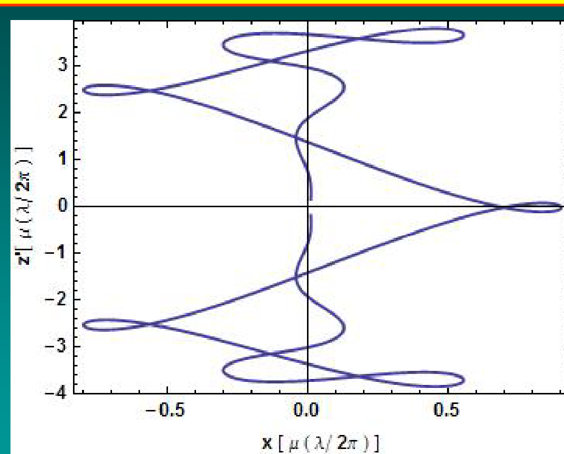
$$m\ddot{x} = -eF_0 \sin\omega t$$

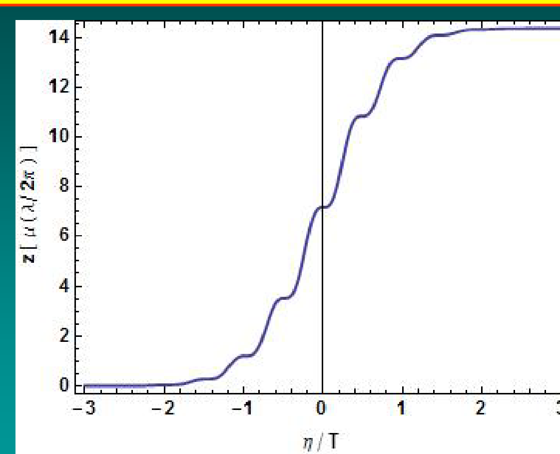
$$eE_c \lambda\!\!\!^{-}_C = \hbar\omega$$

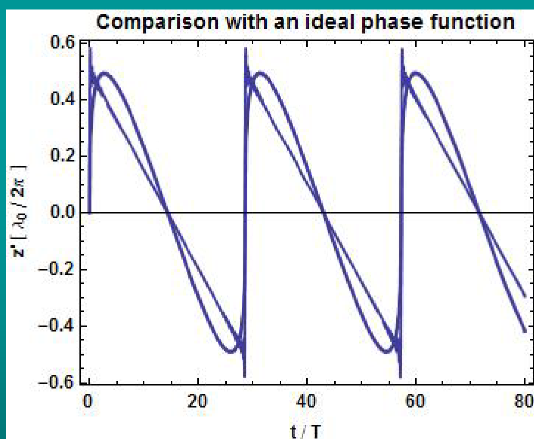
$$\frac{\upsilon_{osc}}{c} = \frac{x_{osc}}{\lambda\!\!\!^{-}} = \mu_0 \equiv \frac{eF_0}{mc\omega} = 8.5\times 10^{-10}\sqrt{I}\cdot\lambda$$

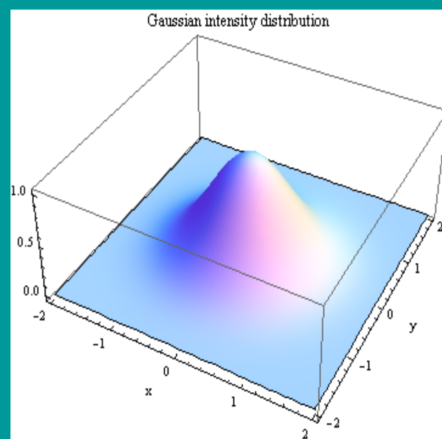
Very distorted trajectories, ‘ponderomotive pushing’, ‘filamentation’

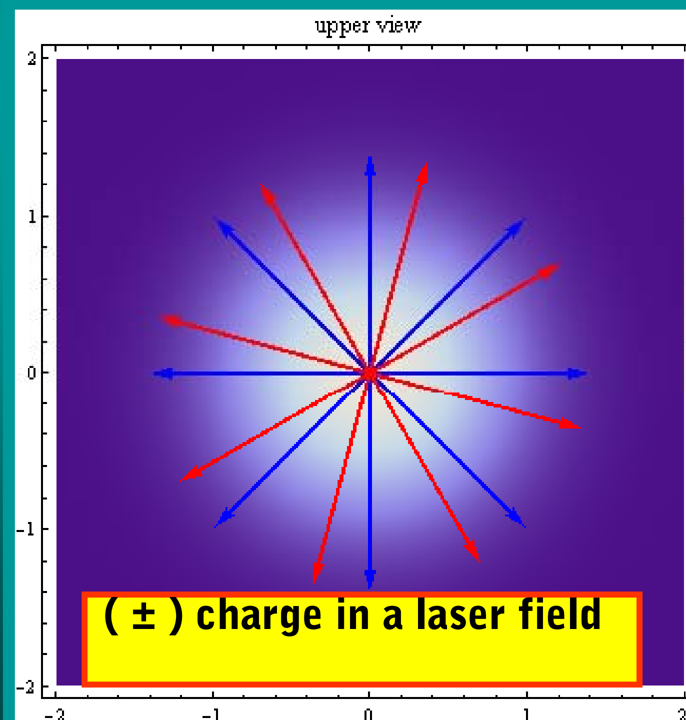












$$U_p(\bar{r})[eV] = 2.5\times10^{-13} I\cdot\lambda^2 e^{-r^2/w^2}$$

See for example : S. V., Intensity effects and absolute phase effects in nonliear laser-matter interactions. *In Laser Pulse Phenomena and Applications* (Ed. F. J. Duarte, InTech Publisher, 2010) Chapter 12, pp. 243-266.

The first: K. SHIMODA [1962]

Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

Among many possible applications of the extremely high brightness temperature and the radiation density obtainable with the optical maser, a high energy electron accelerator is proposed and discussed in this paper. It consists of a cylindrical tube of maser material excited by a pumping radiation through an interference filter coated on its outer surface and, it generates an oscillation in a TM_0NM type mode. An optical peak power of 10 kw/cm² was calculated to accelerate electrons by 10^9 ev/meter. A gas-filled cavity is proposed for velocity matching. Selection of the particular mode might be made by placing a periodically printed absorption layer on the inner surface of the maser cylinder. However, mode separation would be extremely difficult because of thermal expansion of the maser material.

'An optical peak power of 10 kW/cm^2 was calculated to accelerate electrons by 10^9 eV/meter.'

I. Introduction

Directivity, coherence, and brightness temperature of the radiation generated by a high frequency maser are described by the extremely narrow spectral width of the oscillation. When the effect of saturation is neglected, the theoretical width of the spectrum of

frequency. Among many possible applications of an extremely high radiation density obtainable with the optical or infrared maser, an electron linear accelerator is proposed here.

II. Field in a Cylindrical TM_{0NM} Cavity

K. Shimoda, Proposal for an electron accelerator using an optical maser. Applied Optics 1, 33-35 (1962)

K. Shimoda [1962], 'Inverse Cherenkov–Effect'. $1 - \beta n \cos\theta = 0$: the phase of the does not change at the position of the electron, there is no oscillation, but a huge static accelerating (or deccelerating !) field.

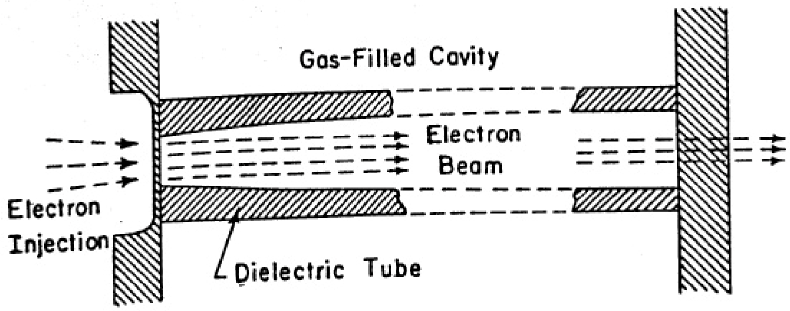


Fig. 2. Dielectric tube in a gas-filled cavity for velocity matching.

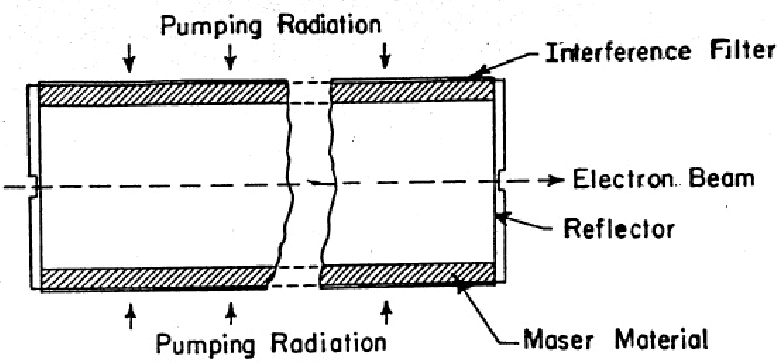


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

electron beam machining.

IV. Conclusion

It has been shown above that an acceleration of 10^9 ev/meter could be obtained with a maser output of 10 kw/cm², if velocity matching and mode selection were achieved. However, with such a large high Q cavity there is likely to exist relaxation oscillation in the maser which must be suppressed.

Mode separation would be very difficult in a cavity especially when thermal expansion is taken into consideration. Beam loading and focusing have not been discussed here. The diameter of the accelerated beam is a fraction of the radial wavelength λ_r, and is about 10^{-3} cm when $\lambda_0 = 10^{-4}$ cm.

Finally, it may be said that the optical maser linac proposed here works on a reverse process of the Čerenkov effect in a gas. One should not be surprised to discover acceleration of electrons in a gas, since the number of collisions in the one-meter path length is roughly the same as that in a conventional synchrotron accelerator if the particle travels about 10^7 meters in a vacuum of about 10^{-5} mm Hg.

Reference

1. K. Shimoda, H. Takahasi, and C. H. Townes, J. Phys. Soc. Japan 12, 686 (1957).

‘(Inverse) Free Electron Laser’ [Palmer, 1972. Madey, 1971] .

Interaction of Relativistic Particles and Free Electromagnetic Waves in the Presence of a Static Helical Magnet*

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Brookhaven National Laboratory, Upton, New York 11973
(Received 23 December 1971)

It is shown that a particle passing along the axis of a helical magnet (in which the field is perpendicular to the axis and rotating as a function of position along the magnet) can be continuously accelerated by its interaction with circularly polarized radiation passing in the same direction. An example is given in which an electron is accelerated to 10 GeV, using a laser of 10^{14} W. A second example shows how pions and kaons might be separated at momenta over 1000 GeV. It is further shown that bunched charged particles passing down the helical magnet will radiate coherent circularly polarized electromagnetic waves, and it is speculated that the required bunching may under some circumstances be self-generating. An example is shown in which a 10-A current of 15-MeV electrons is used to generate a 75-MW beam of 10-μ radiation.

R. Palmer, Interaction of Relativistic Particles and Free Electromagnetic Waves in the Presence of a Static Helical Magnet. J. Applied Physics 43, 3014-3023 (1972)

J. M. J. Madey, Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field. J. Applied Physics 42, 1906-1913 (1971) .

From the recent literature on FEL see e.g.: Varró S (editor), *Free Electron Lasers*. (Rijeka, InTech Publisher, 2012)

Motion of an electron bunch in 'phase space'

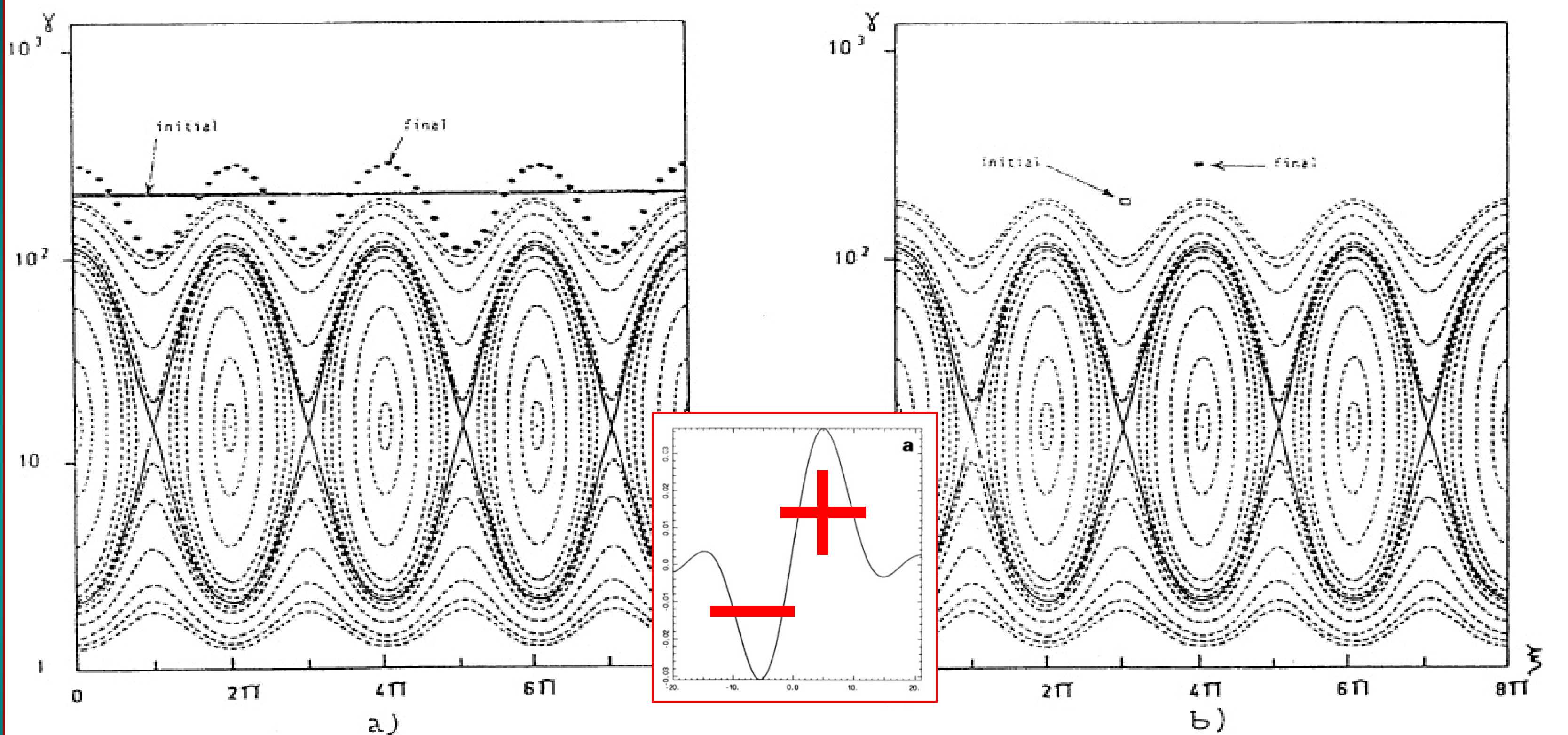


Figure 5.
Phase space behaviour of an electron bunch. a) long bunch, Free Electron Laser regime; b) short bunch, Inverse Free Electron Laser.

Taken from: J. L. Bobin, Plasma assisted inverse free electron laser. In R. Bonifacio, L. De Salvo Souza and C. Pellegrini (Eds.), High gain, high power free electron laser: Physics and application to TeV particle acceleration (North-Holland, Amsterdam, 1989) pp. 197-210.

T. Tajima and J. M. Dawson [1979]: Collective Plasma Accelerator

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2. On the other hand, the glass laser technology is capable of delivering a power density of 10^{18} W/cm^2, and, as we shall see, an electric field of

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \quad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate treatment. Consider the light wave propagating in the x direction with the electric field in the y direction. The light wave sets the electrons

T. Tajima and J. M. Dawson, Laser electron accelerator. *Physical Review Lett.* 43, 267-270 (1979)

'LASER ACCELERATION OF PARTICLES' [Los Alamos, NM, USA, 1982]

AIP Conference Proceedings

Series Editor: Hugh C. Wolfe

Number 91

Laser Acceleration of Particles

(Los Alamos, 1982)

'Renaissance'

Edited by

Paul J. Channell

Los Alamos National Laboratory

Some mechanisms of acceleration viewed as potential candidates high-gradient accelerators are the following (not in order of ority):

1. Grating Accelerator - a special case of a conventional accelerating waveguide in which the waveguide structure is open sided, for example, a diffraction grating in the presence of a strong optical field.
2. High Gradient Structures and Power Sources at Wavelengths Near 1 cm - a scaledown of conventional waveguide structures to millimeter size with emphasis on avoidance of breakdown problems.
3. Inverse Cherenkov Accelerator - relies on index of refraction of background medium to provide phase matching between optical field and electron. A novel geometry has been proposed to alleviate gas-breakdown limitations.
4. Beat-Wave Accelerator - acceleration is achieved by the fields produced as a result of charge separation generated by a traveling plasma wave. The plasma wave, in turn, is set up by a laser pulse whose amplitude is modulated so that the beat frequency matches the plasma frequency.
5. Inverse Free Electron Laser Accelerator - uses the energy exchange occurring when an undulating electron in a periodic magnetic field has a transverse velocity in phase with the transverse E-field of an intense optical beam.
6. Two-Wave Accelerator - similar to (5) except that the magnetic wiggler is replaced by a slow microwave field whose phase velocity relative to the electron beam may be adjusted by changing the relative angle.

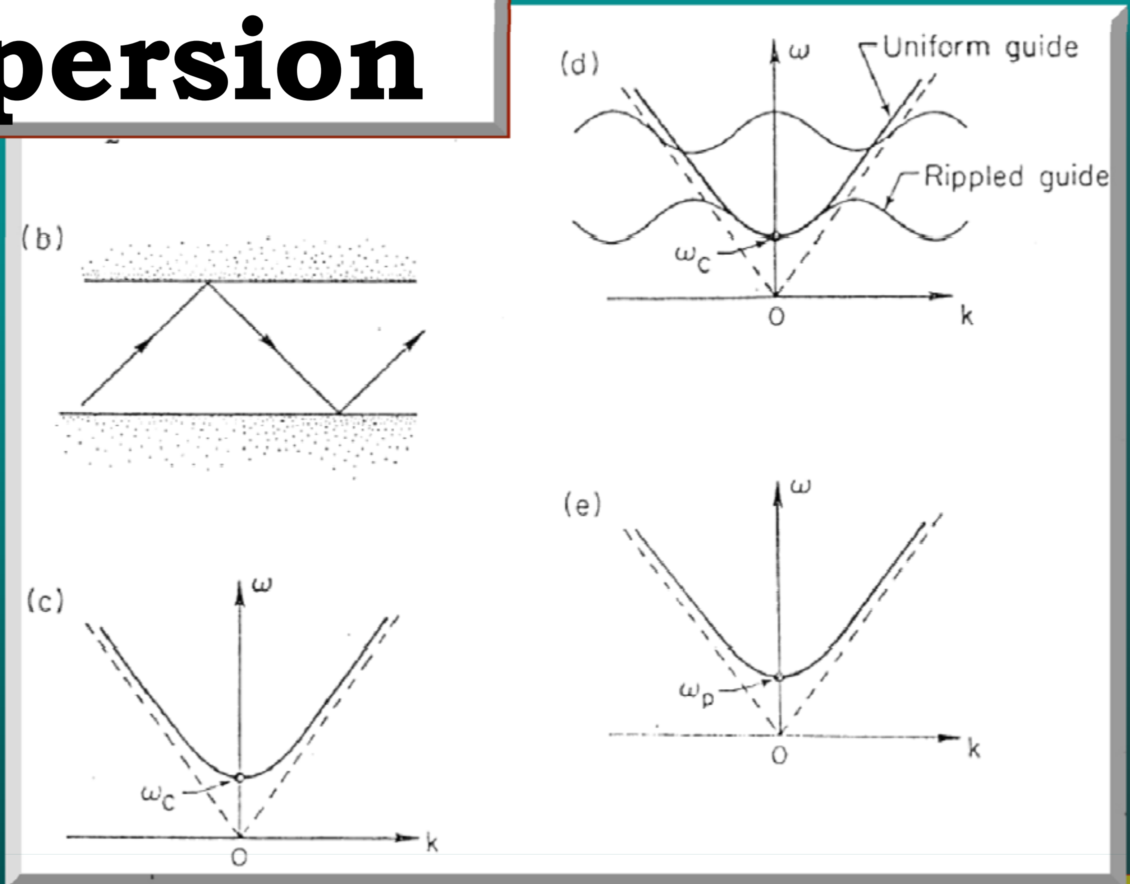
AAC 2012 THE UNIVERSITY OF TEXAS JUNE 10–15, 2

- Laser–Plasma Wakefield Acceleration
- Computations for Accelerator Physics

'Renaissance'

- Laser and High–Gradient Structure–Based Acceleration
- Beam–Driven Acceleration
- Beam and radiation generation, monitoring and control
- Laser–Plasma Acceleration of Ions
- Muon Colliders and Advanced Concepts

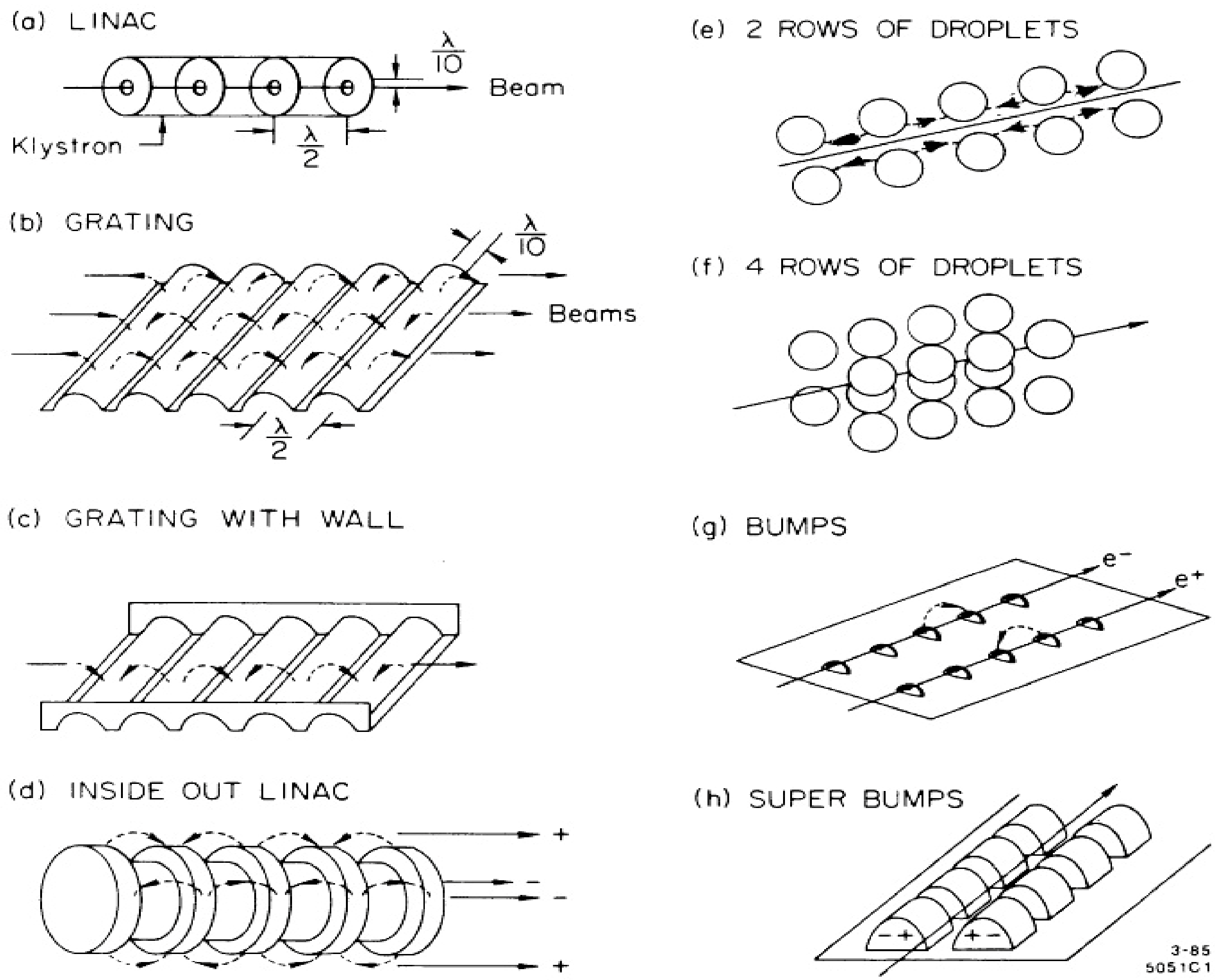
Dispersion



$\omega / c = |\mathbf{k}|$ $\omega = E_p / \hbar$ $\mathbf{k} = \mathbf{p} / \hbar$ $\omega / c = \sqrt{|\mathbf{k}|^2 + \kappa^2}$

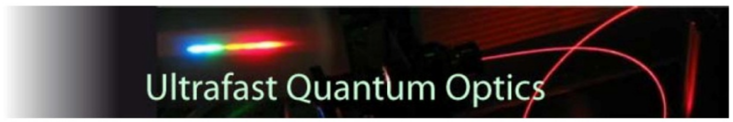
$[F_0 /(V / cm)] = 27.46 \times [I_0 /(W / cm^2)]^{1/2}$ $\kappa \equiv m_e c^2 / \hbar$

‘Near-field accelerating structures’. ‘GRATING LINAC’

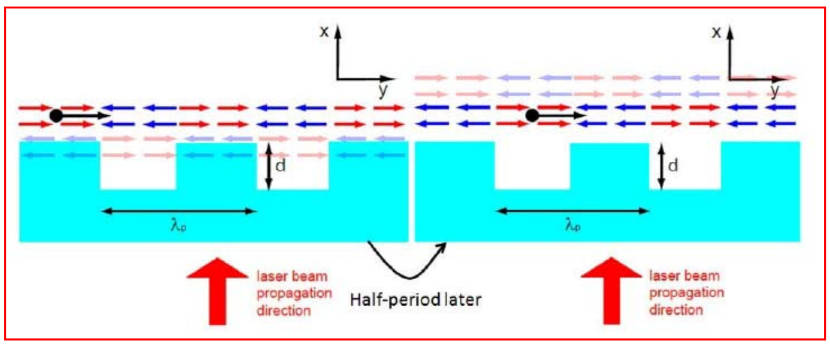


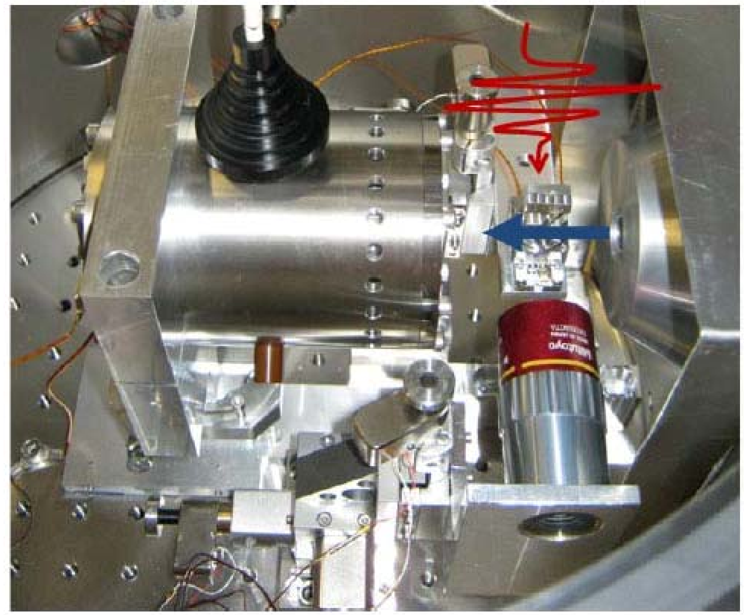
Palmer et al., ‘Report of near field group’. *Laser acceleration of particles* pp234-252 (AIP, N. Y.,1985). Fig.1

‘Near-field accelerating structures’. ‘GRATING LINAC’ [example in 2012]



Electron acceleration with laser light





Electron acceleration with laser light http://www.mpq.mpg.de/cms/mpq/en/groups/hommel/homepage_cms/...

Taken from the homepage: M P Q. Ultrafast Quantum Optics [Head: Peter Hommelhoff]

Not only electrons: Acceleration of protons. [Possible medical applications. 'Hadron therapy']

PRL **109,** 234801 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

Laser-Driven Proton Acceleration Enhancement by Nanostructured Foils

D. Margarone,[1] O. Klimo,[1,2] I. J. Kim,[3] J. Prokůpek,[1,2] J. Limpouch,[1,2] T. M. Jeong,[3] T. Mocek,[1] J. Pšikal,[1,2] H. T. Kim,[3] J. Proška,[2] K. H Nam,[3] L. Štolcová,[1,2] I. W. Choi,[3] S. K. Lee,[3] J. H. Sung,[3] T. J. Yu,[3] and G. Korn[1]

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[2]*Czech Technical University in Prague, FNSPE, Brehova 7, 115 19 Prague, Czech Republic*
[3]*Advanced Photonics Research Institute, GIST, 1 Oryong-dong, Buk-gu, Gwangju 500-712, Republic of Korea*

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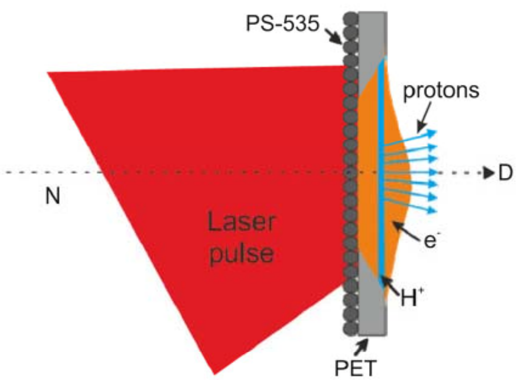


FIG. 1 (color online). TNSA mechanism with the target geometry used in the experiment (side view). The laser beam (*p* polarized) is absorbed at the nanospheres-vacuum interface with an incidence angle of 22.5 degrees (*N* denotes the target normal). The hot electrons (generated at the target front side) propagate forward and accelerate protons at the rear side. The proton or ion diagnostics (*D*) is placed along the *N* direction.

PRL **109,** 234801 (2012) PHYSICAL RE

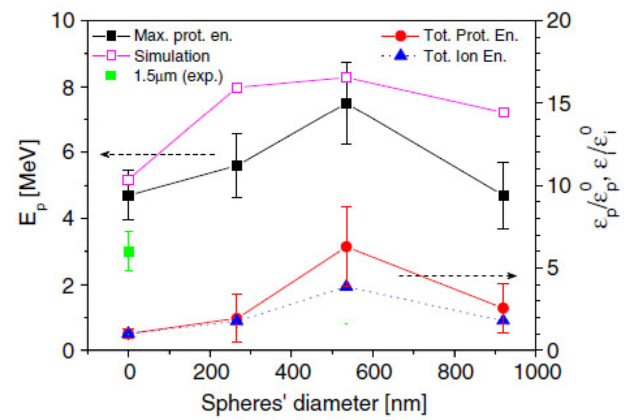
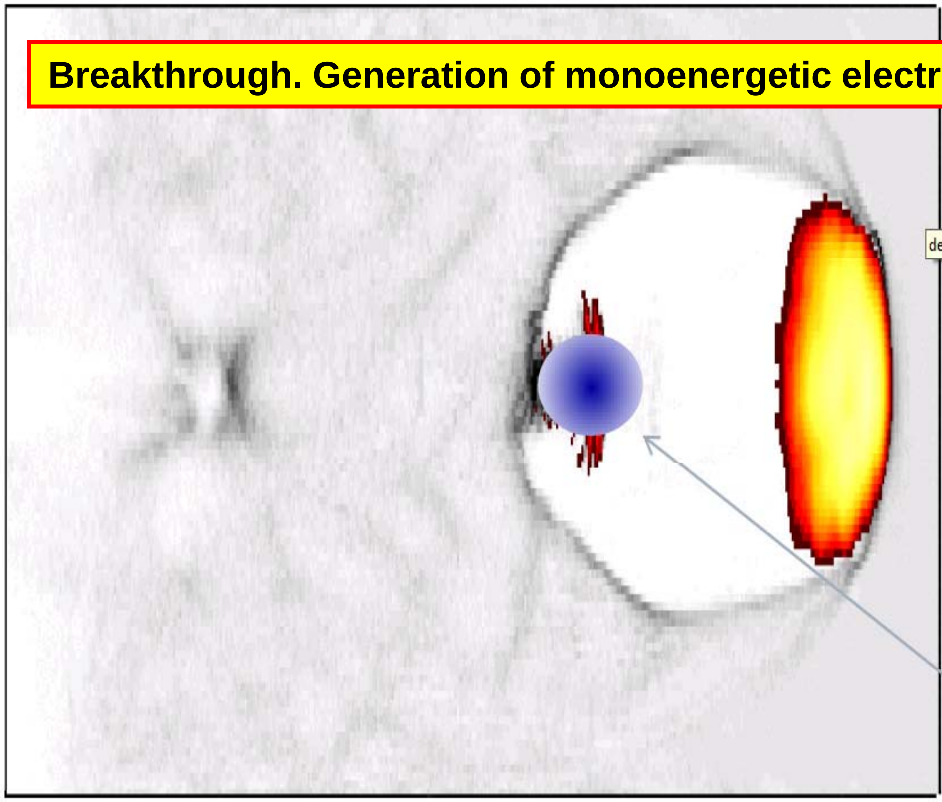
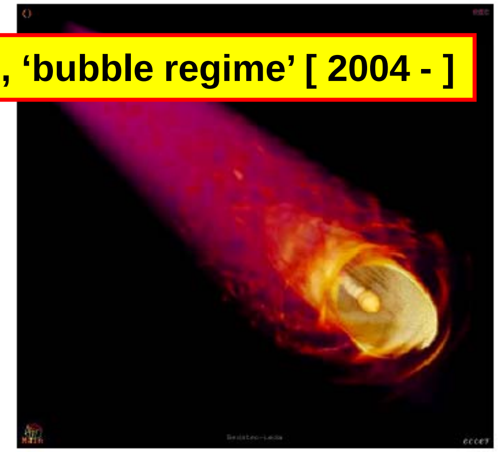
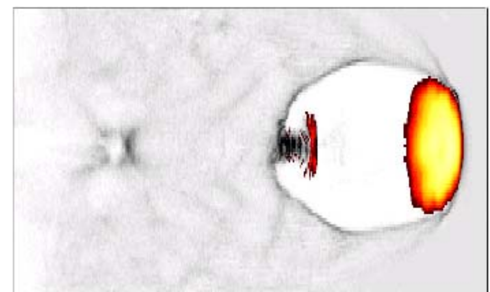


FIG. 4 (color online). Proton beam maximum energy (left-handed axis) and the total energy of the proton and ion beams, each normalized to the case of a planar foil (right-handed axis) for different target geometries.

Breakthrough. Generation of monoenergetic electron beams, ‘bubble regime’ [2004 -]







‘Bubble’ accelerator: A secial wake-field, ‘scalable’ plasma accelerator

Pukhov, Gordienko, Phil Trans. R. Soc. A, (2006) **364**, 623–633

A.Pukhov & J.Meyer-ter-Vehn, *Appl. Phys. B,* **74,** *p*.355 (2002)

J. Faure et al., *Nature* (London) 431, 541 (2004); S. P. D. Mangles et al., *Nature* (London) 431, 535 (2004); C. G. R. Geddes et al., *Nature* (London) 431, 538 (2004); W. P. Leemans et al., *Nat. Phys* 2, 696 (2006); J. Osterhoff et al., *Physical Review Letters* 101, 085002 (2008)

LETTERS

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[3]Nuclear Professional School, University of Tokyo, 22-2 Shirane-shirakata, Tokai, Naka, Ibaraki 319-1188, Japan
*Also at: Physics Department, University of Nevada, Reno, Nevada 89557, USA

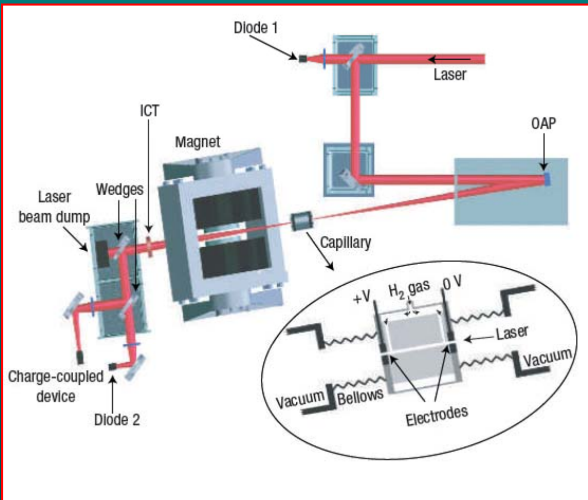
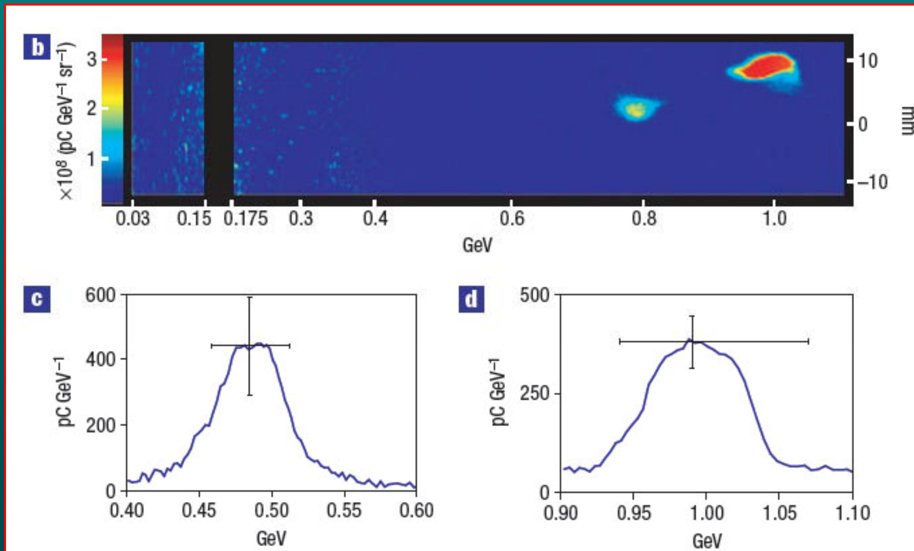
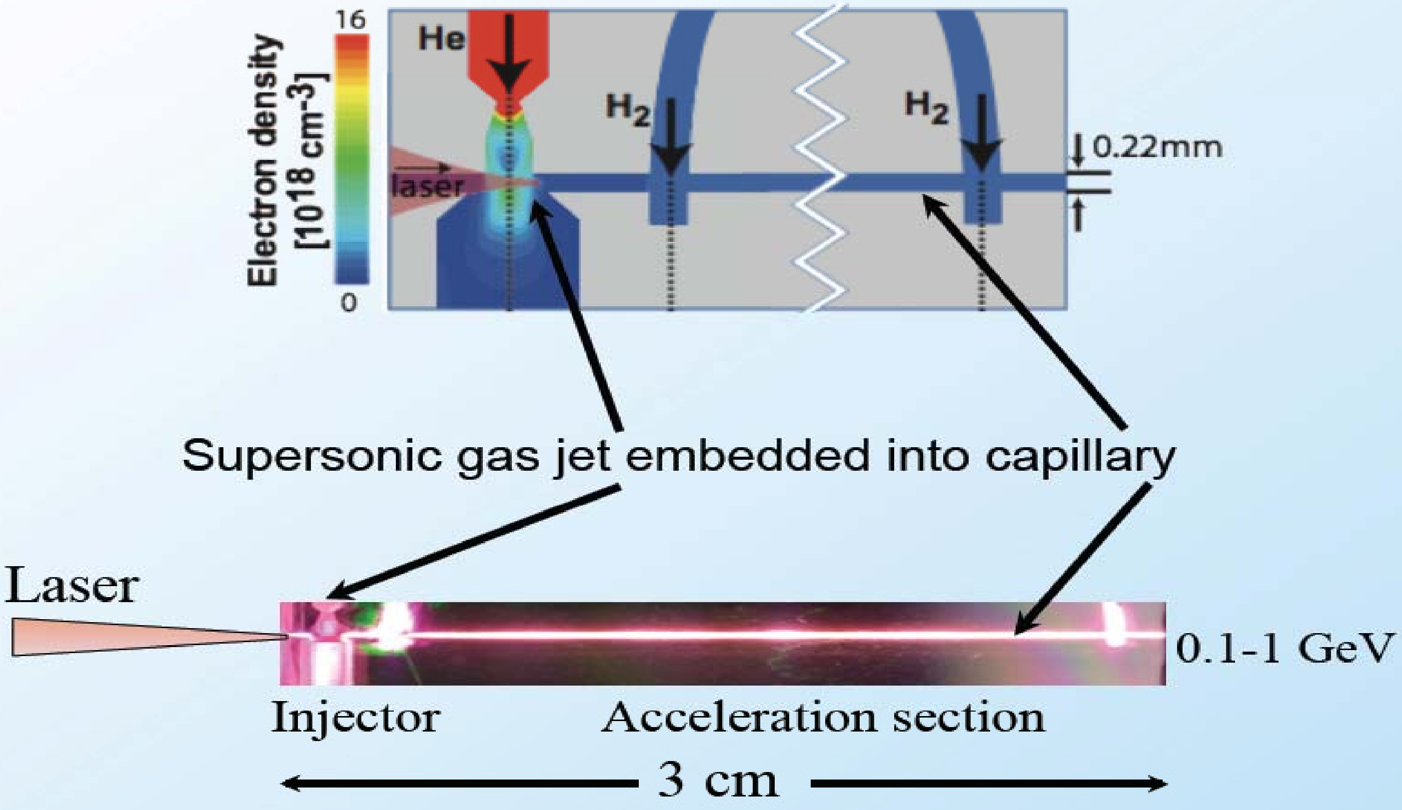


Figure 1 Schematic diagram of the capillary-guided laser-wakefield accelerator. The plasma channel was formed in a hydrogen-filled capillary



W. P. Leemans et al., GeV electron beams from s centimetre-scale accelerator. *Nat. Phys* 2, 696 (2006)

Practical implementation of combined injector and acceleration stage



Picture taken from: Cs. Tóth, Longitudinal density tailoring of a tunable lase plasma accelerator. Presentation at 'LEI-2011' Szeged 2011. [Curtesy Cs Tóth.]

MeV and an intial emittance of 63 mm-mrad. The large input emittance was chosen to maximize the beam radius for efficient beam loading and for emittance matching to the wake's focusing fields [18].

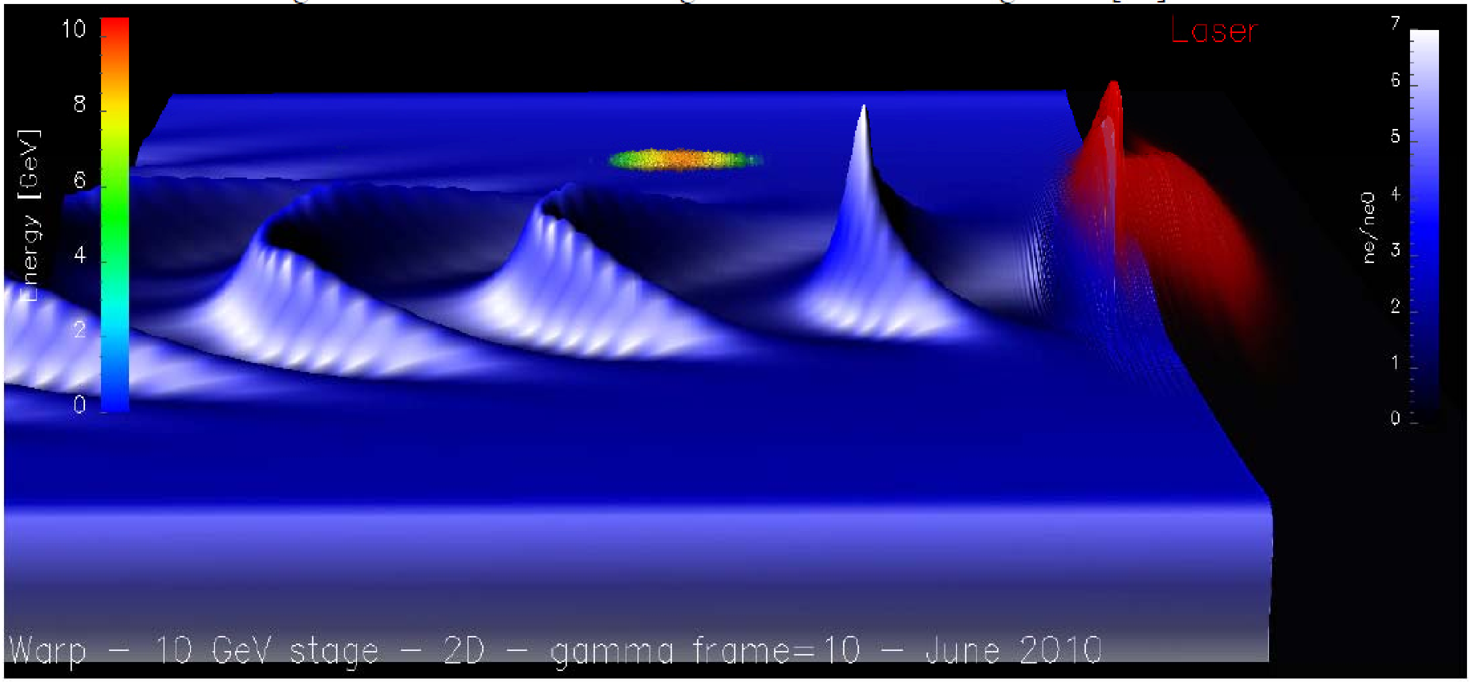


FIGURE 2. Simulation result of a 10 GeV LPA stage from the code WARP3D, using a Lorentz boosted frame. The image shows an externally injected electron bunch (rainbow color) riding a density wake (light blue) excited by an intense laser pulse (red), propagating in a 0.65 m long plasma channel. The laser pulse (~40 J in ~67 fs), focused to ~90 μm spot size at the entrance of the channel, has reached the end of the plasma channel. The electron bunch energy has reached up to ~10 GeV.

Picture taken from: W. P. Leemans, Laser plasma accelerators development and the BELLA Project at LBNL. Presentation at 'LEI-2011' Szeged 2011. [Curtesy Cs Tóth.]

Light Wave Synthesizer 20

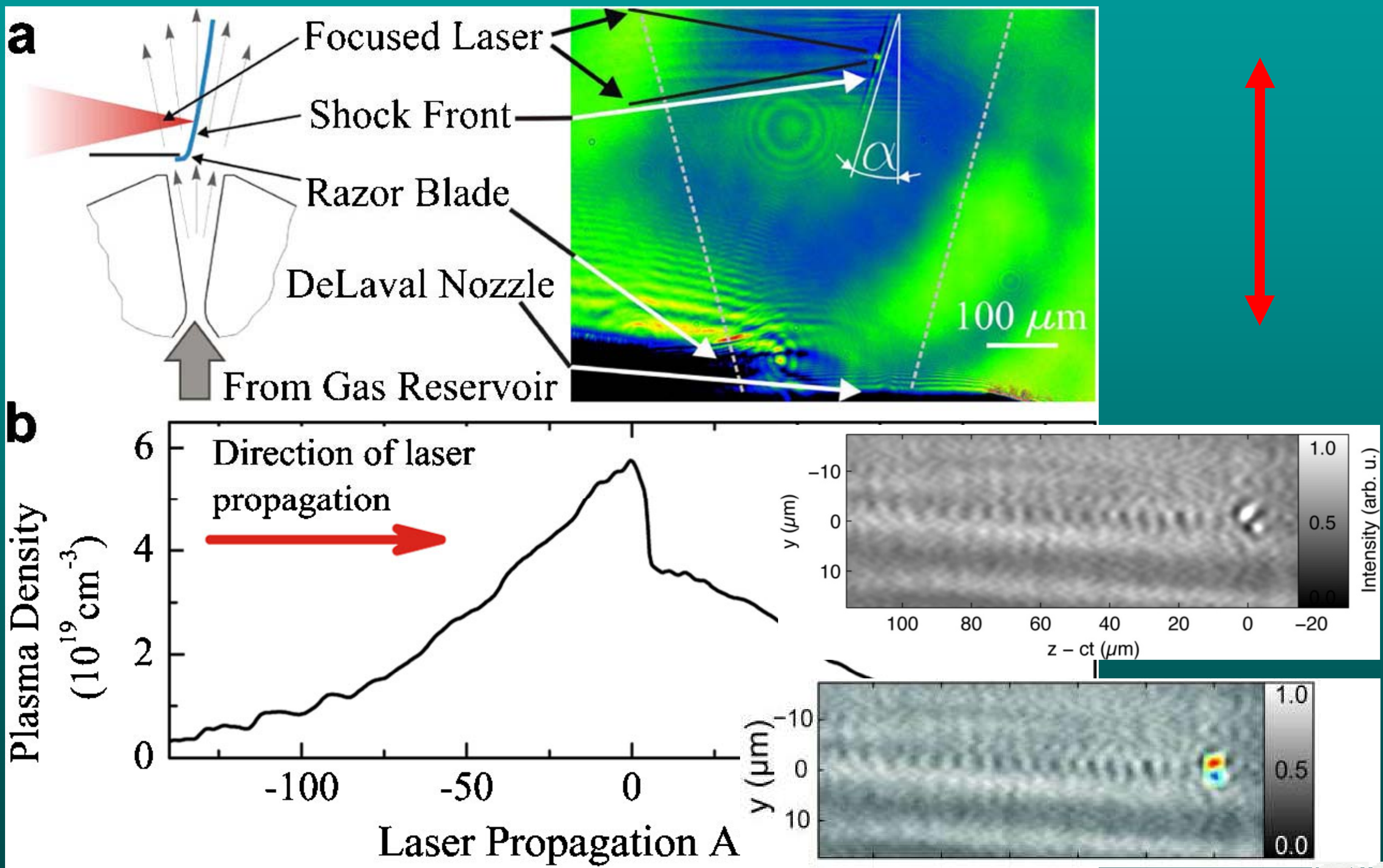
Properties :

Most intense few-cycle laser system in the world!

- **Optical parametric chirped pulse amplifier**
- **80 mJ / pulse**
- **Spectrum: 580-1020nm**
- **Sub-5 fs FWHM pulse duration**
- **16 TW power**
- **10 Hz repetition rate**
- **~10^{20} W/cm^2 peak intensity with F#1 focusing**

László Veisz private communication [MPQ Garching, 5. 12. 2012]

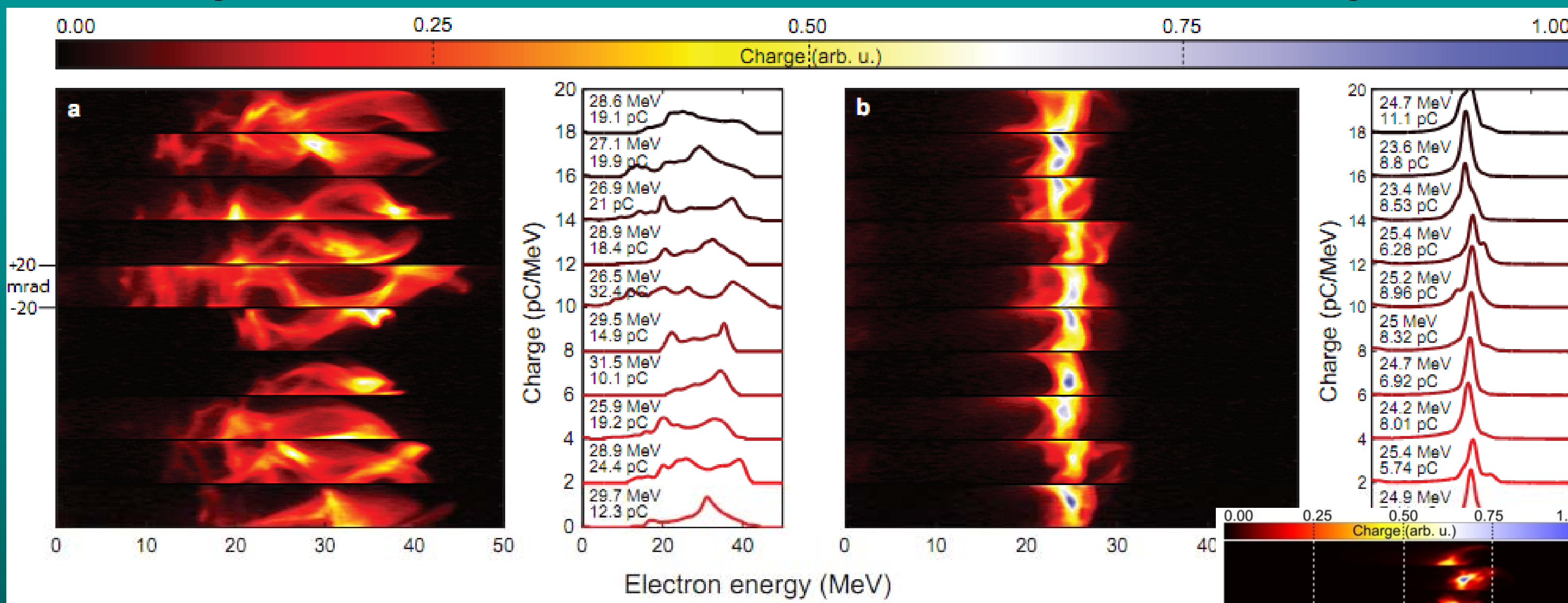
Density transition setup [MPQ, Garching]

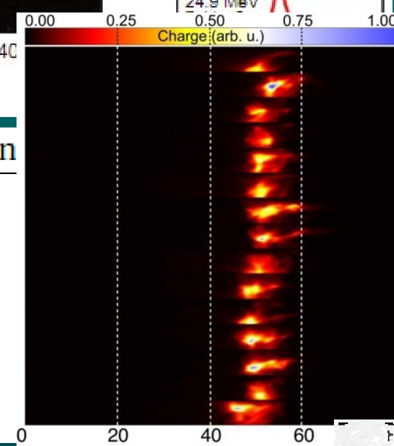


MPQ, Garching: L. Veisz private communication [05. 12. 2012]

Comparison of injection methods [MPQ, Garching]

Self-injection | Controlled injection





Parameter	Self-injection	Density transition injection
Electron energy (MeV)	28.3 ± 1.7	24.3 ± 0.70
Energy spread FWHM (MeV)	20.6 ± 6.7	3.07 ± 0.65
Charge (pC)	19.2 ± 2.0	8.0 ± 1.5
Divergence FWHM (mrad)	20 – 30	20 – 30
Electron density (cm^{-3})	$1.2 \cdot 10^{19}$	$0.6 \cdot 10^{19}$
Injection probability	93 %	99 %

MPQ, Garching: L. Veisz private communication [05. 12. 2012]

Summary

The main problem of laser acceleration of particles is the different dispersion [energy – momentum relation] of light and the massive particles. The history of development in this field is the history of ways how to get around this problem.

The mechanisms of acceleration of charged particles have been systematically studied from the 30ies of the last century (cyclotron, synchrotron, cosmic rays). The radiation loss have been always a chief obstacle. Various techniques from the microwave (in particular, radar) research have been adapted in laser physics [see e.g. mode-loking, picosecond pulses, chirped pulse amplification, attosecond generation by fourier synthesis of very high harmonics]. These are all clear illustrations of the scale-invariance of the Maxwell equations.

There has been no conceptionally new scheeme introduced recently. The basic acceleration mechanisms has already been proposed in the 70-80ies of the last century. Presently the most work is being put to various versions of the plasma wake-field accelerator, like the capillary systems. By now they achieved 1 GeV. For moderate energies and truly table-top setups, the near-field accelerators seem to be the most promising, however they still do not function.

The synchronization of the particles and the accelerating light is a crucial issue. Only recently there has been developments in this respect, and monoenergetic particle beams has been produced with laser light. [For larger energies, quantum statistical and coherence properties and descriptions may be important.]

Appendices

G. A. Schott [1907]; Synchrotron radiation, 'superradiance'

$$(13)\begin{cases} \mathfrak{d}_\theta = \quad h_\psi = \dfrac{2e\beta}{r\varrho} n^2 \cot\theta \displaystyle\sum_{s=1}^{s=\infty} s\, J_{sn}(s\,n\,\beta\sin\theta) \\ \qquad\qquad \sin s\,n\left[\omega\,(t - r/c) + \dfrac{\pi}{2} - \psi\right], \\ \mathfrak{d}_\psi = -\, h_\theta = -\dfrac{2e\beta^2}{r\varrho} n^2 \displaystyle\sum_{s=1}^{s=\infty} s\, J'_{sn}(s\,n\,\beta\sin\theta) \\ \qquad\qquad \cos s\,n\left[\omega\,(t - r/c) + \dfrac{\pi}{2} - \psi\right] \end{cases}$$

in Übereinstimmung mit den anderwärts von mir angegebenen Ausdrücken.[1]) Ferner gibt die Gleichung (12)

$$(14)\begin{cases} S = \dfrac{2\,c\,e^2\beta^2}{\varrho^2} n^4 \displaystyle\sum_{s=1}^{s=\infty} s^2 \int_0^{\pi/2} [\cot^2\theta\,.\,\{J_{sn}(s\,n\,\beta\sin\theta)\}^2 \\ \qquad\qquad + \beta^2\{J'_{sn}(s\,n\,\beta\sin\theta)\}^2]\sin\theta\,d\theta. \end{cases}$$

§ 8. Dieser Ausdruck kann mittels des Neumannschen Additionstheorems vereinfacht werden; es ist

$$\{J_{sn}(x)\}^2 = \frac{1}{\pi}\int_0^{\pi} J_0(2\,x\sin\varphi)\cos 2\,s\,n\,\varphi\,d\varphi,$$

G. A. Schott, Über die Strahlung von Elektronengruppen. Annalen der Physik (4) 635-660 (1907)

Cosmic rays. Acceleration by microwaves [E. M. McMillan 1945, 1950]

PHYSICAL REVIEW VOLUME 79, NUMBER 3 AUGUST 1, 1950

The Origin of Cosmic Rays

EDWIN M. MCMILLAN
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
(Received January 31, 1950)

The original idea of Menzel and Salisbury concerning the origin of cosmic rays has been extended and some of its possible consequences worked out in more detail. It is concluded that low frequency electromagnetic waves (a few cycles per second) may exist in limited regions near the outer edge of the solar corona, and could accelerate ions to cosmic-ray energies. An attempt is made to explain both the "ordinary" cosmic
s in terms of the action of these waves.

Radiation from a Group of Electrons Moving in a Circular Orbit

EDWIN M. MCMILLAN
University of California, Berkeley, Californ
September 9, 1945

A SINGLE electron of total energy E (rest
moving in a circle of radius R, radiates e
rate L (electron volts per turn), given by:

$$L=400\pi(e/R)(E/E_r)^4,$$

where e is the electronic charge in e.s.u., and
the synchrotron one has the case of a rather
group of electrons moving in the orbit, an
amount of radiation depends on the coherence
waves emitted by the individual electrons. Fo
there were complete coherence, the radiation
would be N times that given by (1), where N is
of electrons in the group.

It is apparent from the above that an an
coherence problem is very important for an
which groups of electrons are made to mov
with high velocity. This answer is given by a
to J. Schwinger (communicated to the auth
Rabi). Schwinger's formula gives the radia
harmonic of the period of revolution, in a form
easy computation for any distribution of elec
the orbit. It leads to the following conclusions

PHYSICAL REVIEW VOLUME 79, NUMBER 3 AUGUST 1, 1950

The Extraordinary Increase of Cosmic-Ray Intensity on November 19, 1949

SCOTT E. FORBUSH
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
AND
THOMAS B. STINCHCOMB AND MARCEL SCHEIN
Department of Physics, University of Chicago, Chicago, Illinois
(Received April 20, 1950)

Four sudden increases in cosmic-ray intensity associated with solar flares or chromospheric eruptions have so far been observed during more than a decade of continuous registration of cosmic-ray intensity. The last and largest of these increases occurred on November 19, 1949, when such an effect was recorded for the first time at a mountain station at Climax, Colorado. Here the intensity increased to about 200 percent above normal in half an hour. At the sea-level station at Cheltenham, Maryland, the increase was about 43 percent. No increase occurred at the equator. From the increase in the effect with altitude and latitude, it is concluded that the increase was due to the nucleonic component produced by relatively low energy primary charged particles probably accelerated by some solar mechanism.

Fermi, Teller, Alfvén, McMillan,...The origin of cosmic rays. What kind of acceleration mechanism ?

‘RADIATION LABORATORY’ [Cambridge, Mass., 1940–1945.]

PRINCIPLES OF MICROWAVE CIRCUITS

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OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
NATIONAL DEFENSE RESEARCH COMMITTEE

FIRST EDITION
SECOND IMPRESSION

RADIATION·LABORATORY·M·I·T·CAMBRIDGE·MASS·1940·1945

NEW YORK · TORONTO · LONDON
McGRAW-HILL BOOK COMPANY, INC.
1948

Foreword

The tremendous research and development effort that went into the development of radar and related techniques during World War II resulted not only in hundreds of radar sets for military (and some for possible peacetime) use but also in a great body of information and new techniques in the electronics and high-frequency fields. Because this basic material may be of great value to science and engineering, it seemed most important to publish it as soon as security permitted.

The Radiation Laboratory of MIT, which operated under the supervision of the National Defense Research Committee, undertook the great task of preparing these volumes. The work described herein, however, is the collective result of work done at many laboratories, Army, Navy, university, and industrial, both in this country and in England, Canada, and other Dominions.

The Radiation Laboratory, once its proposals were approved and finances provided by the Office of Scientific Research and Development, chose Louis N. Ridenour as Editor-in-Chief to lead and direct the entire project. An editorial staff was then selected of those best qualified for this type of task. Finally the authors for the various volumes or chapters or sections were chosen from among those experts who were intimately familiar with the various fields, and who were able and willing to write the summaries of them. This entire staff agreed to remain at work at MIT for six months or more after the work of the Radiation Laboratory was complete. These volumes stand as a monument to this group.

These volumes serve as a memorial to the unnamed hundreds and thousands of other scientists, engineers, and others who actually carried on the research, development, and engineering work the results of which are herein described. There were so many involved in this work and they worked so closely together even though often in widely separated laboratories that it is impossible to name or even to know those who contributed to a particular idea or development. Only certain ones who wrote reports or articles have even been mentioned. But to all those who contributed in any way to this great cooperative development enterprise, both in this country and in England, these volumes are dedicated.

L. A. DuBridge.

A 'Nobel example': The microwave technique and the 'Lamb shift' [1947]

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

Fine Structure of the Hydrogen Atom by a Microwave Method* **

WILLIS E. LAMB, JR. AND ROBERT C. RETHERFORD
Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York

(Received June 18, 1947)

THE spectrum of the simplest atom, hydrogen, has a fine structure[1] which according to the Dirac wave equation for an electron moving in a Coulomb field is due to the combined effects of relativistic variation of mass with velocity and spin-orbit coupling. It has been considered one of the great triumphs of Dirac's theory that it gave the "right" fine structure of

population and the high background absorption due to electrons. Instead, we have found a method depending on a novel property of the $2^2S_{\frac{1}{2}}$ level. According to the Dirac theory, this state exactly coincides in energy with the $2^2P_{\frac{1}{2}}$ state which is the lower of the two P states. The S state in the absence of external electric fields is metastable. The radiative transition to the

The calculated separation between the levels $2^2P_{\frac{1}{2}}$ and $2^2P_{3/2}$ is 0.365 cm^{-1} and corresponds to a wave-length of 2.74 cm. The great wartime advances in microwave techniques in the vicinity of three centimeters wave-length make possible the use of new physical tools for a study of the $n=2$ fine structure states of the hydrogen atom. A little consideration shows that it would be exceedingly difficult to detect the direct absorption of radiofrequency radiation by excited H atoms in a gas discharge because of their small

or may be brought about by the Zeeman splitting of the levels in an external magnetic field.

In brief, the experimental arrangement used is the following: Molecular hydrogen is thermally dissociated in a tungsten oven, and a jet of atoms emerges from a slit to be cross-bombarded by an electron stream. About one part in a hundred million of the atoms is thereby excited to the metastable $2^2S_{\frac{1}{2}}$ state. The metastable atoms (with a small recoil deflection) move on out of the bombardment region and are detected by the process of electron ejection from a metal target. The electron current is measured with an FP-54 electrometer tube and a sensitive galvanometer.

If the beam of metastable atoms is subjected to

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University, New York.
** Work supported by the Signal Corps under contract number W 36-039 sc-32003.

Undulator radiation, 'Free electron laser' [H. Motz, 1951,1953]

Journal of Applied Physics

Volume 22, Number 5 May, 1951

Applications of the Radiation from Fast Electron Beams

H. Motz
Microwave Laboratory, Stanford University, California
(Received July 3, 1950)

The radiation from fast electron beams passing through a succession of electric or magnetic fields of alternating polarity is examined. The radiation of maximum frequency is emitted in the forward direction. If the deflecting fields are not too large, a semiqualitative argument shows that the maximum frequency is the lowest possible harmonic. The frequencies emitted are determined by studying the Doppler effect, and the angular distribution of radiated energy as well as the total radiation are calculated in a simple straightforward manner with reference to well-known formulas of special relativity. The question of the coherence of the radiation is discussed. The spectral distribution of radiated energy is then calculated more exactly. It is concluded that several applications of the radiation appear possible. A scheme for obtaining millimeter-waves of considerable power is outlined. The upper limit of the power in a band extending down to a wavelength of 1 millimeter is calculated to be of the order of several kilowatts for a beam of one ampere and an energy of 1.5 megavolt. The use of the radiation for speed monitoring of beams with energies up to 1000 megavolt is discussed.

Undulator radiation, 'Free electron laser' [H. Motz, 1951,1953]

angle of observation. The fundamental component of the radiation emitted under the angle θ (see Fig. 1) has a frequency

$$\omega = \Omega_\theta = 2\pi\beta c / l_0 (1 - \beta \cos\theta). \qquad (1)$$

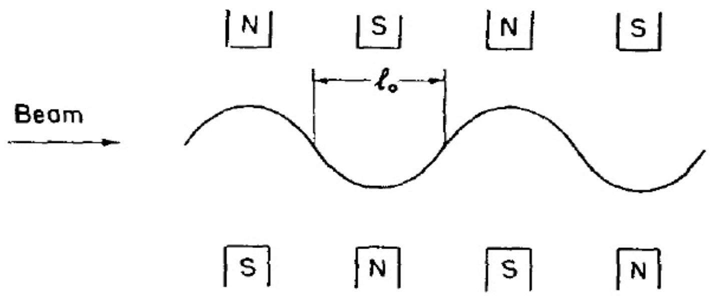


FIG. 1. Schematic arrangement of undulator magnets.

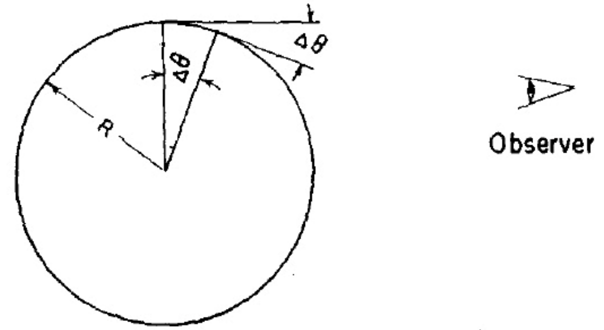


FIG. 2. Illustrates the radiation cone emanating from an electron in a circular orbit.

In the extreme relativistic case, when the electron velocity is near the velocity of light and the accelerations ... decelerations suffered by the electrons in the pe... field are considerable, most of the energy is in a ... harmonic of this fundamental frequency, which is ... mined by the maximum instantaneous acceleration or deceleration.[1] However, even for extremely

The energy radiated per unit area into the pth harmonic of Ω_θ is given by

$$\frac{1}{(1-\beta\cos\theta)^2}\left(\frac{\omega}{\Omega_\theta}\right)^2 \frac{e^2\beta^2 S_p{}^2}{4\pi^2 r^2 c}\Big\{\sin^2\theta[J_p(Z)]^2 + \tfrac{1}{4}\sin^2 X[J_{p+1}(Z)+J_{p-1}(Z)]^2 \cdot \frac{e^2\mathcal{E}^2 l_0{}^2(1-\beta^2)}{4\pi^2\beta^2(m_0c^2)^2}\Big\}. \qquad (66)$$

The result obtained by putting $p=0$ deserves special mention. It is very small in our case. However, it is this term which would give the contribution of the Cerenkov effect to the total energy radiated if the undulator were filled with a medium of refractive index $\epsilon^{\frac{1}{2}}$. In this case,

Power radiated coherently thus becomes

$$(\tfrac{1}{5}\cdot 10^8)^2 2\cdot 10^{-15} 3\cdot 10^{11} = 2.4\cdot 10^{11}\ \text{erg/sec} = 2.4\cdot 10^4\ \text{watts},$$

while the power radiated incoherently would have been $1.2\cdot 10^{-3}$ watts. However, if it were possible to bunch all the electrons contained in one-cm length of beam into $\frac{1}{2}$-millimeter bunches, we should get $2.4\cdot 10^5$ watts radiated coherently.

Undulator radiation, 'Free electron laser' [H. Motz, 1951,1953]

The energy radiated per unit area into the pth harmonic of Ω_θ is given by

$$\frac{1}{(1-\beta\cos\theta)^2}\left(\frac{\omega}{\Omega_\theta}\right)^2 \frac{e^2\beta^2 S_p{}^2}{4\pi^2 r^2 c}\left\{\sin^2\theta[J_p(Z)]^2 + \tfrac{1}{4}\sin^2 X[J_{p+1}(Z)+J_{p-1}(Z)]^2\cdot\frac{e^2\mathcal{E}^2 l_0{}^2(1-\beta^2)}{4\pi^2\beta^2(m_0c^2)^2}\right\}. \quad (66)$$

The result obtained by putting $p=0$ deserves special mention. It is very small in our case. However, it is this term which would give the contribution of the Cerenkov effect to the total energy radiated if the undulator were filled with a medium of refractive index $\epsilon^{\frac{1}{2}}$. In this case,

IV. GENERATION OF VISIBLE LIGHT

1. The Basic Experiment

It follows from Eq. (1) that an electron beam with an energy 100 Mev passing through the undulator

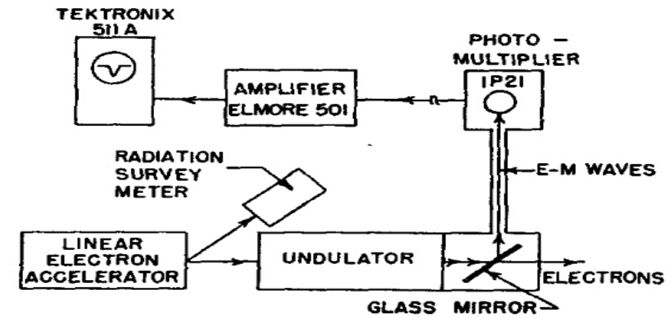


FIG. 4. Detector arrangement for light waves.

should generate visible light. Such a beam energy was available to us for a short period from the Stanford linear accelerator. The following experiment was carried out. The undulator was connected vacuumwise to the accelerator. At the exit end of the undulator the wave guide was closed by a thin glass plate (microscope cover glass). A mirror made of microscope cover slide on which silver had been evaporated was placed to intercept any light coming through the window. According to the equation

$$\theta = m_0c^2/E,$$

where E is the beam energy, this light would arrive under an angle of 1/200 radian. Using a selsyn drive the mirror could be rotated by remote control. At an angle of 45° with the beam the mirror would reflect the light onto the photosurface of a photomultiplier tube (Fig. 4). The photomultiplier worked into a cathode follower and a long cable to a remote oscilloscope.

The γ-ray and neutron intensity near the undulator was rather large, and direct visual observation was therefore impossible. The γ-rays also caused a background signal from the photomultiplier, which was considerably reduced by careful lead shielding of the tube. We observed a pulse on the scope, corresponding to the pulsed operation of the accelerator, when the mirror was inclined 45°. The pulse disappeared when this angle was changed by a few degrees in either direction. The signal disappeared also when the electron beam was magnetically deflected and thus prevented from entering the undulator. We regard these observations as clear evidence that the undulator indeed generated a beam of light.

A. Schawlow , C. Townes, 'Optical Maser' (1958)

PHYSICAL REVIEW VOLUME 112, NUMBER 6 DECEMBER 15, 1958

Infrared and Optical Masers

A. L. SCHAWLOW AND C. H. TOWNES*
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received August 26, 1958)

The extension of maser techniques to the infrared and optical region is considered. It is shown that by using a resonant cavity of centimeter dimensions, having many resonant modes, maser oscillation at these wavelengths can be achieved by pumping with reasonable amounts of incoherent light. For wavelengths much shorter than those of the ultraviolet region, maser-type amplification appears to be quite impractical. Although use of a multimode cavity is suggested, a single mode may be selected by making only the end walls highly reflecting, and defining a suitably small angular aperture. Then extremely monochromatic and coherent light is produced. The design principles are illustrated by reference to a system using potassium vapor.

INTRODUCTION

AMPLIFIERS and oscillators using atomic and molecular processes, as do the various varieties of masers,[1-4] may in principle be extended far beyond the range of frequencies which have been generated electronically, and into the infrared, the optical region, or beyond. Such techniques give the attractive promise of coherent amplification at these high frequencies and of generation of very monochromatic radiation. In the infrared region in particular, the generation of reasonably intense and monochromatic radiation would allow the possibility of spectroscopy at very much higher resolution than is now possible. As one attempts to extend maser operation towards very short wavelengths, a number of new aspects and problems arise, which require a quantitative reorientation of theoretical discussions and considerable modification of the experimental techniques used. Our purpose is to discuss theoretical aspects of maser-like devices for wavelengths considerably shorter than one centimeter, to examine the short-wavelength limit for practical devices of this type, and to outline design considerations for an example of a maser oscillator for producing radiation in the infrared region. In the general discussion, roughly reasonable values of design parameters will be used. They will be justified later by more detailed examination of one particular atomic system.

* Permanent address: Columbia University, New York, New York.
[1] Gordon, Zeiger, and Townes, Phys. Rev. 99, 1264 (1955).
[2] Combrisson, Honig, and Townes, Compt. rend. 242, 2451 (1956).
[3] N. Bloembergen, Phys. Rev. 104, 329 (1956).
[4] E. Allais, Compt. rend. 245, 157 (1957).

CHARACTERISTICS OF MASERS FOR MICROWAVE FREQUENCIES

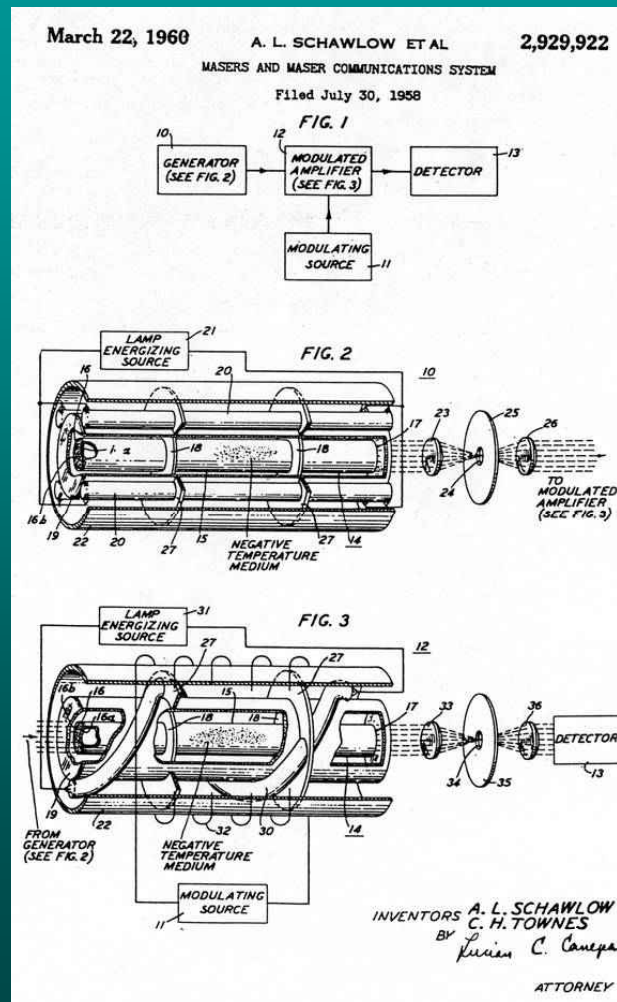
For comparison, we shall consider first the characteristics of masers operating in the normal microwave range. Here an unstable ensemble of atomic or molecular systems is introduced into a cavity which would normally have one resonant mode near the frequency which corresponds to radiative transitions of these systems. In some cases, such an ensemble may be located in a wave guide rather than in a cavity but again there would be characteristically one or a very few modes of propagation allowed by the wave guide in the frequency range of interest. The condition of oscillation for n atomic systems excited with random phase and located in a cavity of appropriate frequency may be written (see references 1 and 2)

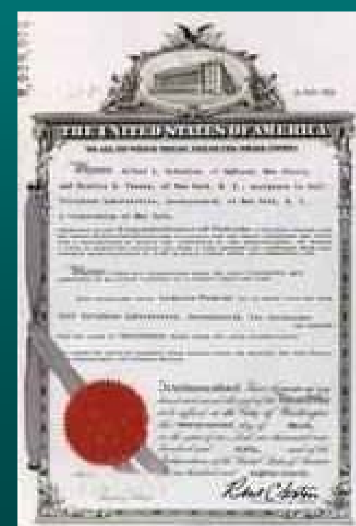
$$n \geq kV\Delta\nu/(4\pi\mu^2 Q_c), \qquad (1)$$

where n is more precisely the difference $n_1 - n_2$ in number of systems in the upper and lower states, V is the volume of the cavity, $\Delta\nu$ is the half-width of the atomic resonance at half-maximum intensity, assuming a Lorentzian line shape, μ is the matrix element involved in the transition, and Q_c is the quality factor of the cavity.

The energy emitted by such a maser oscillator is usually in an extremely monochromatic wave, since the energy produced by stimulated emission is very much larger than that due to spontaneous emission or to the normal background of thermal radiation. The frequency range over which appreciable energy is distributed is given approximately by[1]

$$\delta\nu = 4\pi kT(\Delta\nu)^2/P, \qquad (2)$$





Th. Maiman, 'Optical maser': 'Ruby laser' (1960)

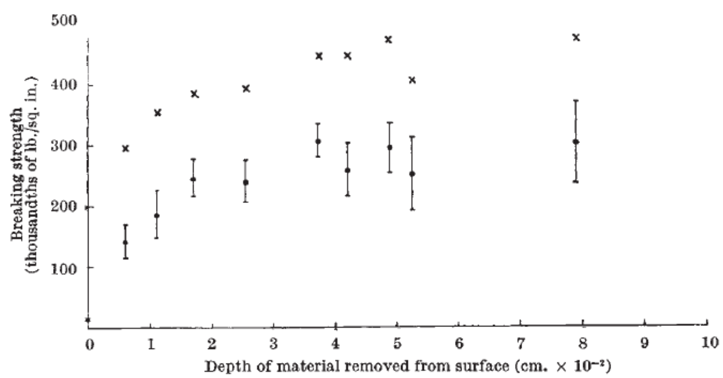


Fig. 1. Breaking strength as a function of depth of material removed from the surface. ×, Highest strength value in one group of rods; ●, mean strength and 95 per cent confidence limits for one group of rods

particular etching solution removes material from a glass surface it is possible to study the strength of etched specimens as a function of the depth of material removed from the surface. Such a study may give some information about the size and nature of the surface imperfections.

Commercially available soda-glass rods, of 6–8 mm. diameter, have been etched and broken in four point bending over a constant bending moment span of 1 in. The rod diameters and loads at fracture were measured and the breaking stresses calculated using the simple bending formula. Groups of rods (containing 16–32 rods) were given different periods of etching, and the depth of material removed from the surface of the rods was calculated for each group.

The variation of the mean breaking strength of these groups of rods, with depth of material removed from the surface, is shown in Fig. 1. Also shown on Fig. 1 are the 95 per cent confidence limits on the mean strength and the highest strength value recorded in each group of rods. Fig. 2 is a histogram comparing the distribution of breaking stresses for a group of rods which have been etched for 40 min. with that for unetched rods. The maximum strengths obtained with these bulk glass specimens are in the region 450,000–500,000 lb./sq. in. and closely approach the value obtained by Thomas[2] for fine glass fibres.

The glass rod used in these experiments had the following approximate composition by weight (percentages): SiO_2, 69; Na_2O, 16; CaO, 4; Al_2O_3, 3; MgO, 3.

The etching solution contained about 15 per cent hydrofluoric acid, 15 per cent sulphuric acid by weight and the remainder water.

Experiments are being continued to determine the effect on these results of varying the concentration, temperature and nature of the etchant; and of changing the thermal history, size and composition of the glass.

B. A. Proctor

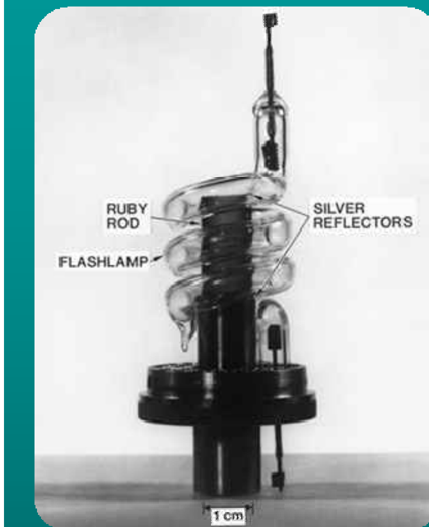
Rolls-Royce, Ltd.,
Aerophysics Laboratory,
Littleover,
Derby.

June 22.

[1] Greene, C. H., *J. Amer. Cer. Soc.*, **39**, 66 (1956).
[2] Thomas, W. F., *Nature*, **181**, 1006 (1958); *Phys. and Chem. Glasses*, **1**, 4 (1960).

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).



‘Free Electron Laser’ [Madey, 1971] . (‘Laser’ + ‘Large facility’) Physics’

JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

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Physics Department, Stanford University, Stanford, California 94305

(Received 20 February 1970; in final form 21 August 1970)

The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

At least two authors have considered in detail the process of induced bremsstrahlung at radio and optical frequencies due to the scattering of an electron beam by the ion cores in neutral and ionized matter concluding that appreciable gain was available under favorable conditions.[1–3] This analysis deals with the radiation emitted by a relativistic electron beam moving through a periodic transverse dc magnetic field. We will consider the process as the scattering of virtual photons using the Weizsäcker–Williams method[4] to relate the transition rates to the more easily calculable rates for Compton

where

$$\beta \equiv v_z/c$$

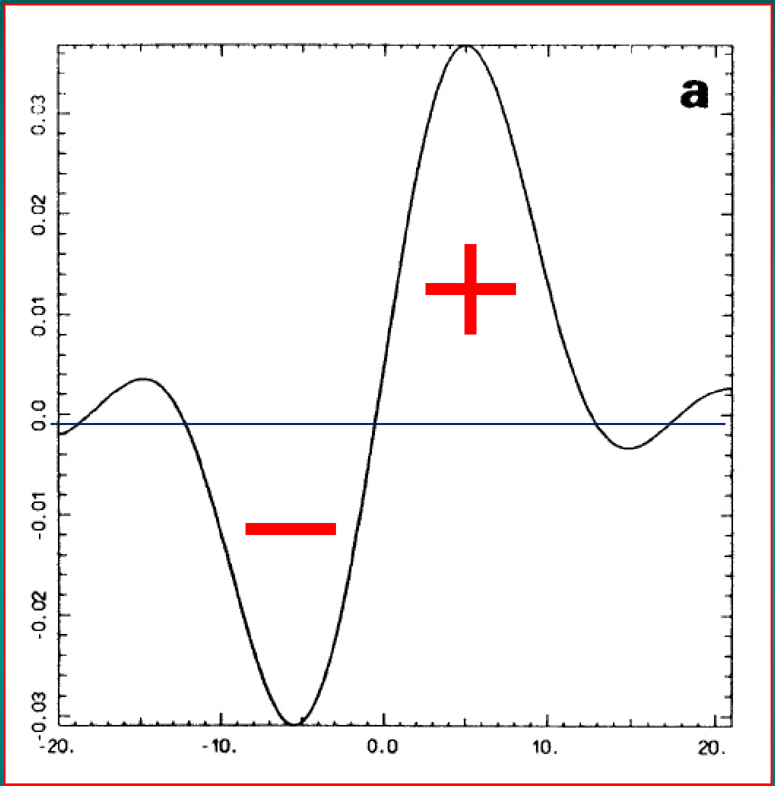
and

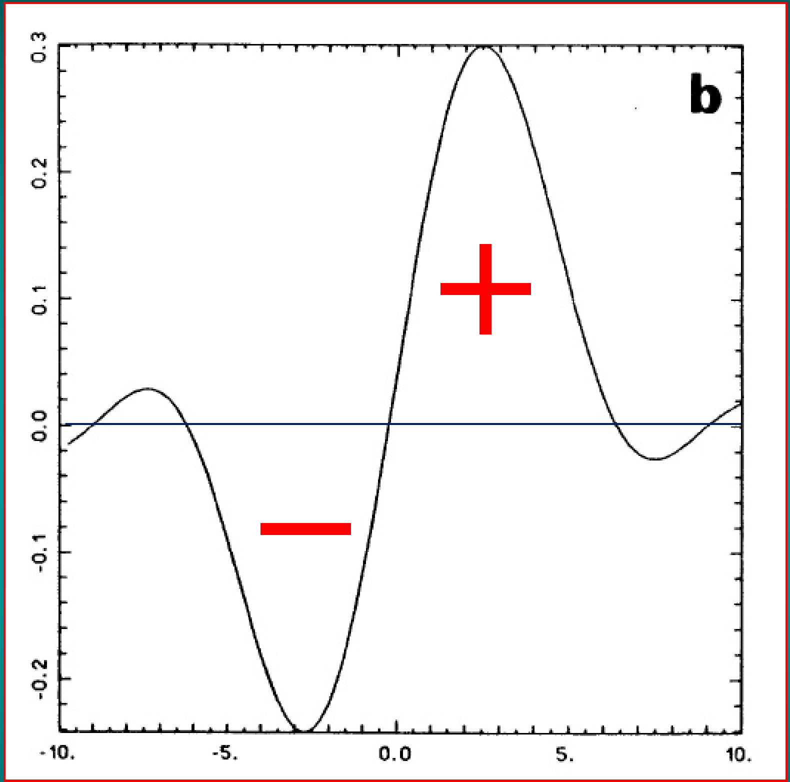
$$\gamma \equiv 1/(1-\beta^2)^{1/2}.$$

In the limit $\beta \to 1$ these fields approach in detail those associated with a wave packet of real photons moving in the direction $-\hat{\mathbf{z}}'$. Assuming that the matrix element for scattering is a continuous and slowly changing function of the initial photon mass, in the limit that the photon energy in the electron rest frame is large in comparison with the photon mass excess, the mass zero expressions

J. M. J. Madey, Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field. J. Applied Physics 42, 1906-1913 (1971)

The gain of the Free Electron Laser can be positive or negative → Inverse F.E.L.





$$\lambda_s \approx \lambda_w \frac{1+K^2}{2\gamma^2}$$

$$\Delta \equiv 4\pi N_w \frac{\gamma_0 - \gamma_r}{\gamma_r}$$

$$G \propto \frac{1}{\Delta^3}\left(1 - \cos\Delta - \frac{\Delta}{2}\sin\Delta\right)$$

‘Inverse Free Electron Laser [Palmer, 1972] .

TABLE I. Parameters of a 10-GeV electron accelerator.

Fixed parameters			
Laser power if single image		P	10^{14} W
Electric field		E_0	$\approx 1.7\times10^{8}$ V/cm
Wavelength of radiation		λ	10^{-4} cm
Helical magnetic field		B_0	10^{4} G
Length		L	200 m
Diameter of optical image		ρ	≈ 1 cm
Variable parameters		**At injection**	**Final**
Electron energy	w	≈ 50 MeV	10 GeV
Length of one turn of the helix	Λ	≈ 1 cm	50 cm
Helix angle	α	$\approx 10\times10^{-3}$ rad	2×10^{-3} rad
Rate of energy gain	$\frac{dw}{dz}$	≈ 1.7 MeV/cm	0.35 MeV/cm
Bunching length	l	≈ 10 cm	20 m

J. Appl. Phys., Vol. 43, No. 7, July 1972

R. Palmer, Interaction of Relativistic Particles and Free Electromagnetic Waves in the Presence of a Static Helical Magnet. J. Applied Physics 43, 3014-3023 (1972)

LASER ACCELERATION OF PARTICLES [Malibu, CA, USA, 1985]

AIP Conference Proceedings
Series Editor: Rita G. Lerner
Number 130

Laser Acceleration of Particles

(Malibu, California, 1985)

Edited by
Chan Joshi and Thomas Katsouleas
University of California, Los Angeles

PREFACE

The second workshop on "Laser Acceleration of Particles," was held at the Norton Simon Malibu Beach Conference Center of the University of California, Los Angeles from January 7-18, 1985. The Chairman of the organizing committee was Dr. Lee Teng of Fermilab.

This book contains most of the invited presentations and contributed papers by the attendees. The executive summary by Dr. Lee Teng and the working group summaries provide overviews of the present state of the field on laser acceleration of particles and can serve as introductions for the nonexpert. In addition to the working group summaries, a basic overview of laser technology and accelerator technology is provided by the laser and accelerator tutorials. These reflect the effort to establish and unite (at least through common language) a joint scientific community with the diverse backgrounds that laser acceleration of particles involves. The tutorials should provide a valuable reference to researchers who have not specifically worked in both disciplines.

The proceedings of the first workshop on Laser Acceleration of Particles, held at Los Alamos in February 1982, were also published as AIP Conference Proceedings, No. 91, edited by P. Channell. The workshop and these proceedings were supported by the Office of Energy Research of the U.S. Department of Energy, the National Science Foundation, the American Physical Society and UCLA. Special thanks are due to Dr. David Sutter of the DOE and Dr. David Berley of the NSF for support and encouragement, and to Ms. Maria Gonzales for help with the organizational details.

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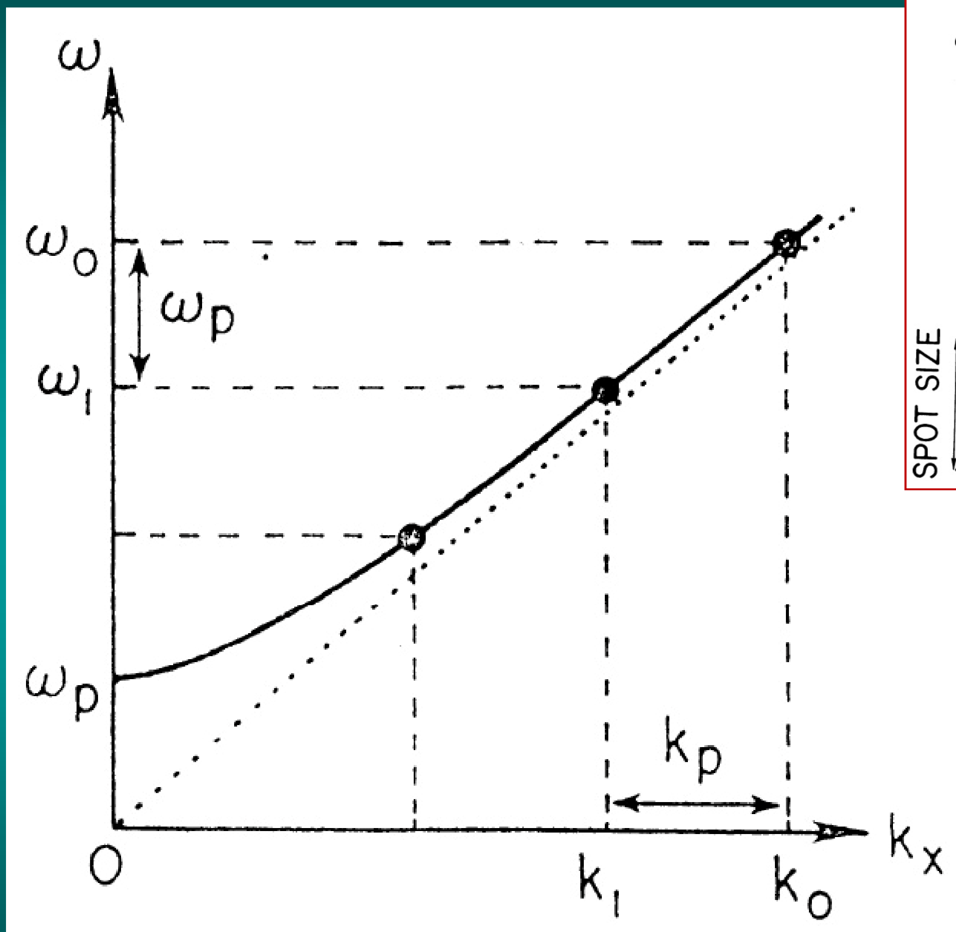
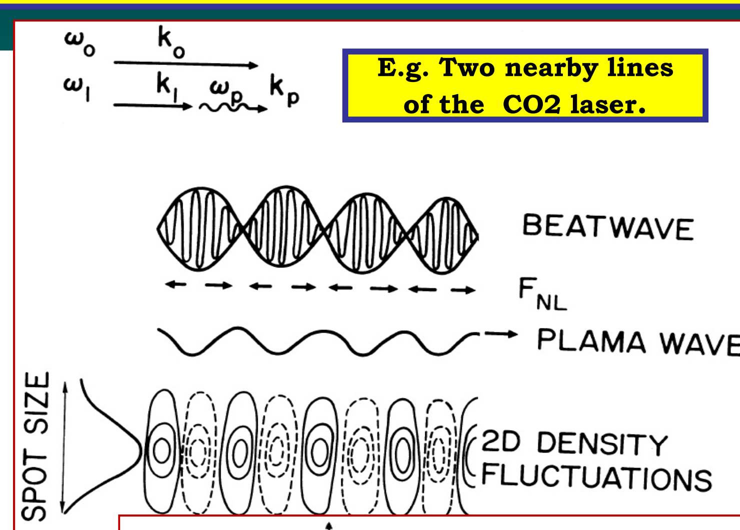
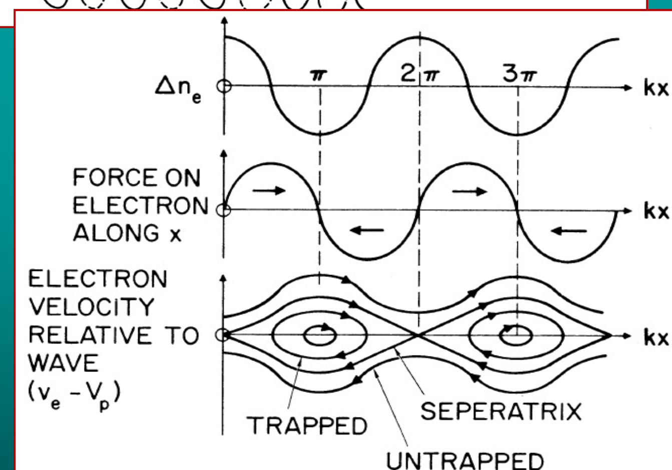
Plasma beat-wave accelerator. Trapping in strong quasi-static field.

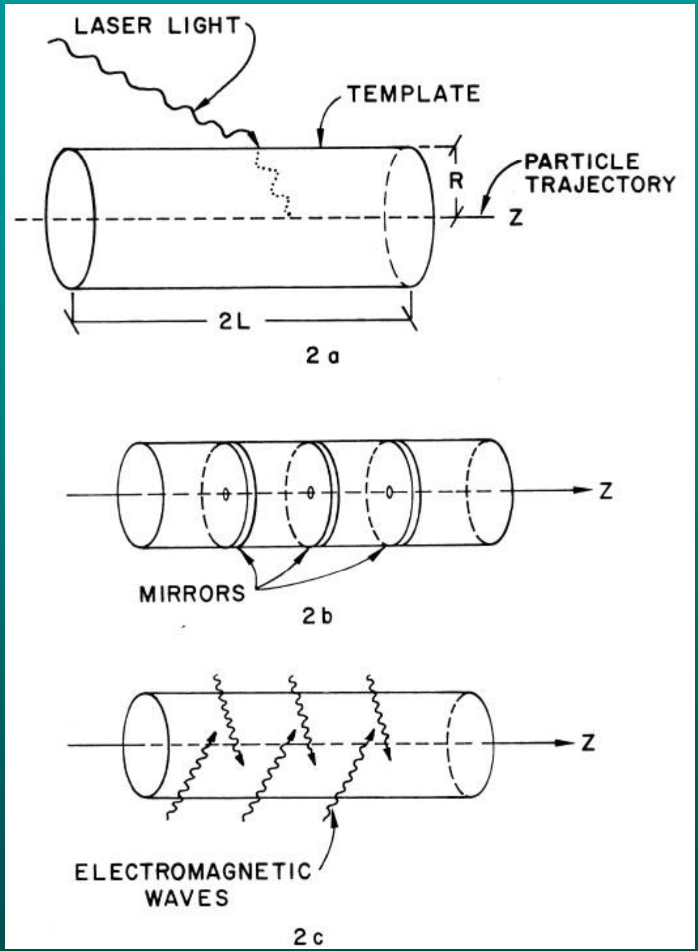


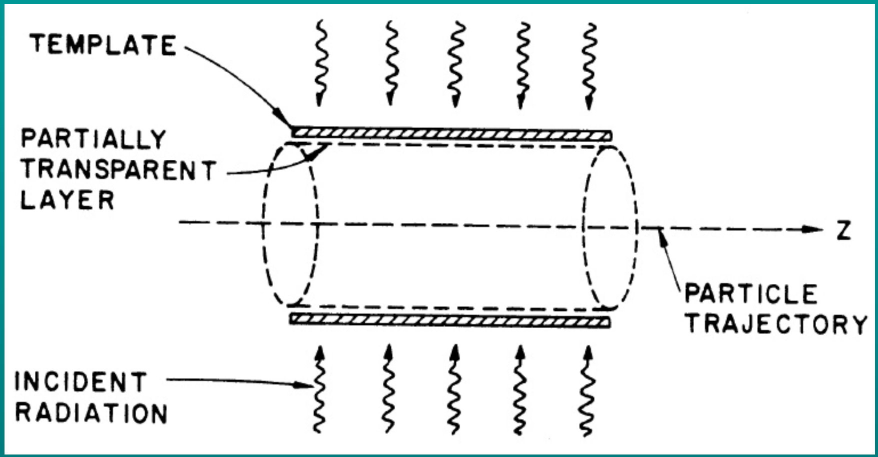




Taken from: C. Joshi, The plasma beat wave accelerator. Pp. 28-43. T. Tajima and J. M. Dawson, Laser acceleration by plasma waves. In Paul J. Channel (Ed.), *Laser Acceleration of Particles*. (Los Alamos, 18-23 February1982) (AIP Conference Proceedings No. 91, AIP, NY, 1982) pp.69-93.

How to get around the problem of different dispersion properties ?





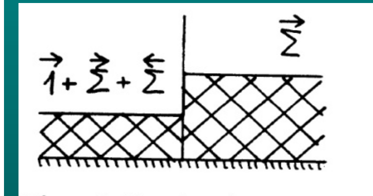
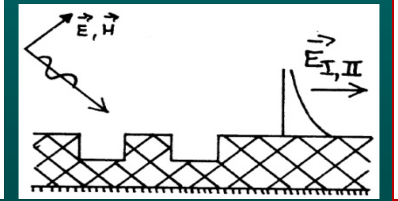


Fig. 7 The basic problem to be solved for calculating the coupling



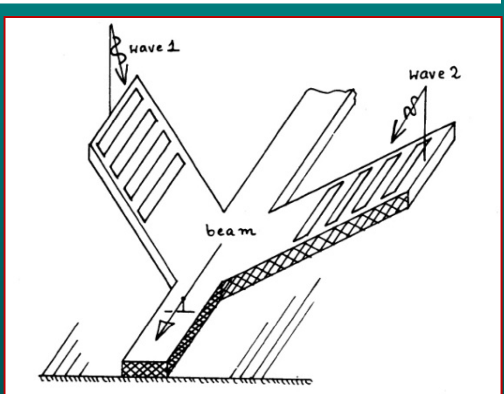
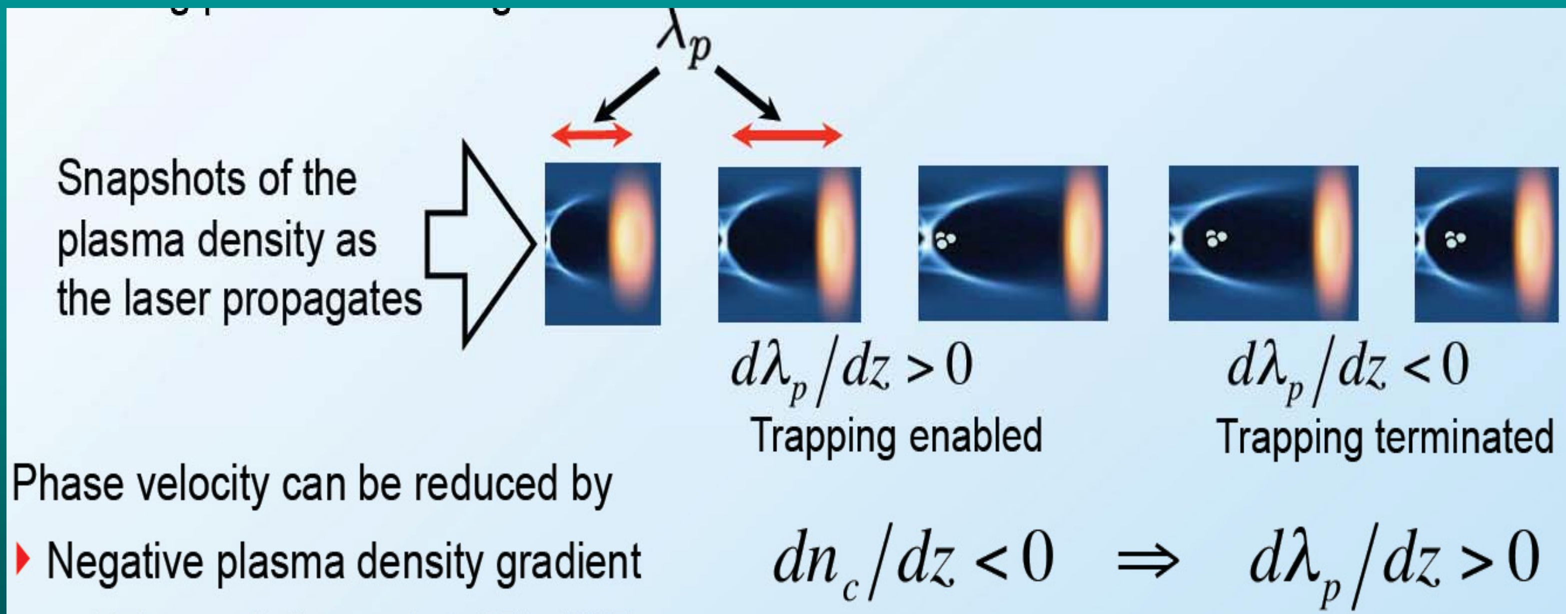


Fig.8 A laser accelerator feeding in the light over two side lines. The strip lines are used to focus and steer the light towards the beam line in the center

Paul L. Csonka, „Near field" laser accelerators. In Paul J. Channel (Ed.), Laser Acceleration of Particles. (Los Alamos, 18-23 February1982) (AIP Conference Proceedings No. 91, AIP, NY, 1982) pp.213-236. AND: T. Weiland, Thin layer dielectric near field laser accelerator. Ibid. pp. 203-210.

Plasma wake – field accelerator. ‘BELLA Project’



Picture taken from: Cs. Tóth, Longitudinal density tailoring of a tunable lase plasma accelerator. Presentation at ‘LEI-2011’ Szeged 2011.

TABLE 1. Example of a design of a Quasilinear 10 GeV BELLA stage and the scaled scaled simulations.

Laser & Plasma Parameters	BELLA 10 GeV	10x density
Laser Energy [J]	40	1.8
a_0	1.4	1.4
λ_p [μm]	107.5	34
$k_p L_{laser}$	1	1
L_{laser} [fs]	57	18
w_0 [μm]	91.4	28.9
P [TW]	554	55
$k_p w_0$	5.3	5.3
P/P_c	1.7	1.7
Linear Dephasing length [m]	0.97	0.03
Pump depletion length [m]	1.98	0.06
Stage length in simulation[m]	0.6	0.0019
Energy gain in simulation	10	1

Picture taken from: W. P. Leemans, Laser plasma accelerators development and the BELLA Project at LBNL. Presentation at 'LEI-2011' Szeged 2011.