ELECTRONS ACCELERATION

in an

INVERTED MEDIUM

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Outline

- Overview and Motivation
- Particle Acceleration in Inverted Medium
- Wake Amplification and Acceleration
- Parameter Analysis
- Experimental Setup
- Summary

Overview

Laser & Plasma

- *Laser Wake-Field*
- *Plasma Beat-Wave*

Laser & Inverse of Radiation Processes

- *Inverse Cerenkov*
- *Inverse FEL*
- *Inverse Smith-Purcell*

E-beam & Plasma

- *Wake-Field Acc.*

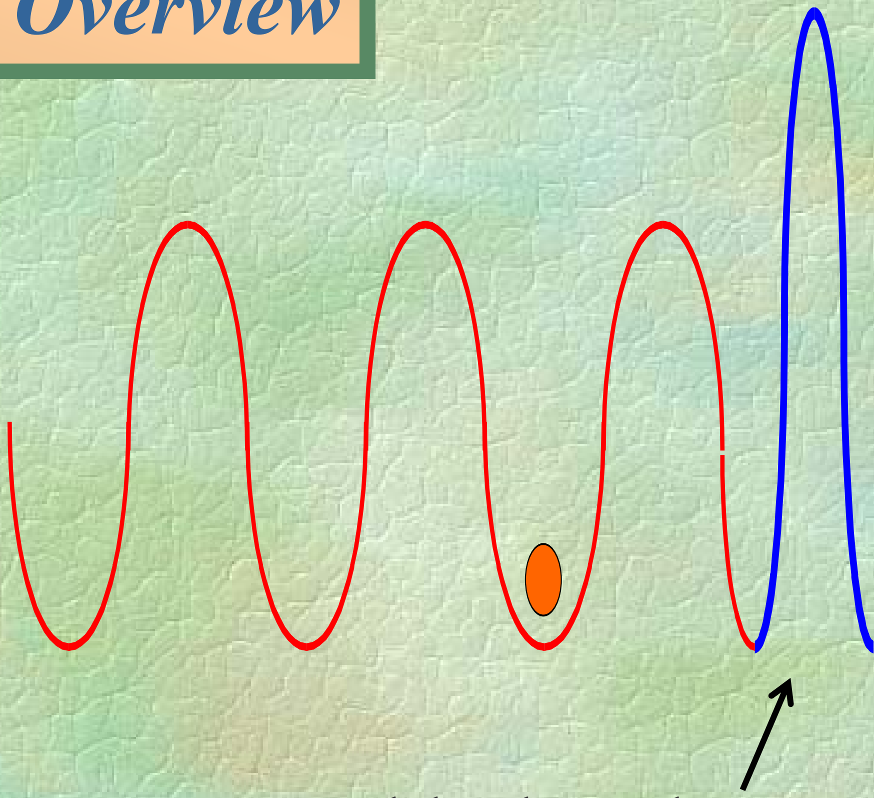
E-beam & Structure

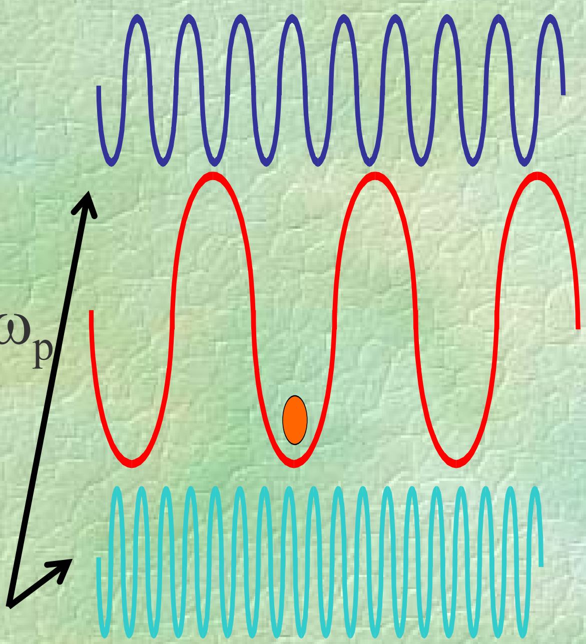
- *Two-Beam Acc.*
- *Cerenkov Wake-Field*

Overview

Laser & Plasma

- *Laser Wake-Field*
- *Plasma Beat-Wave*

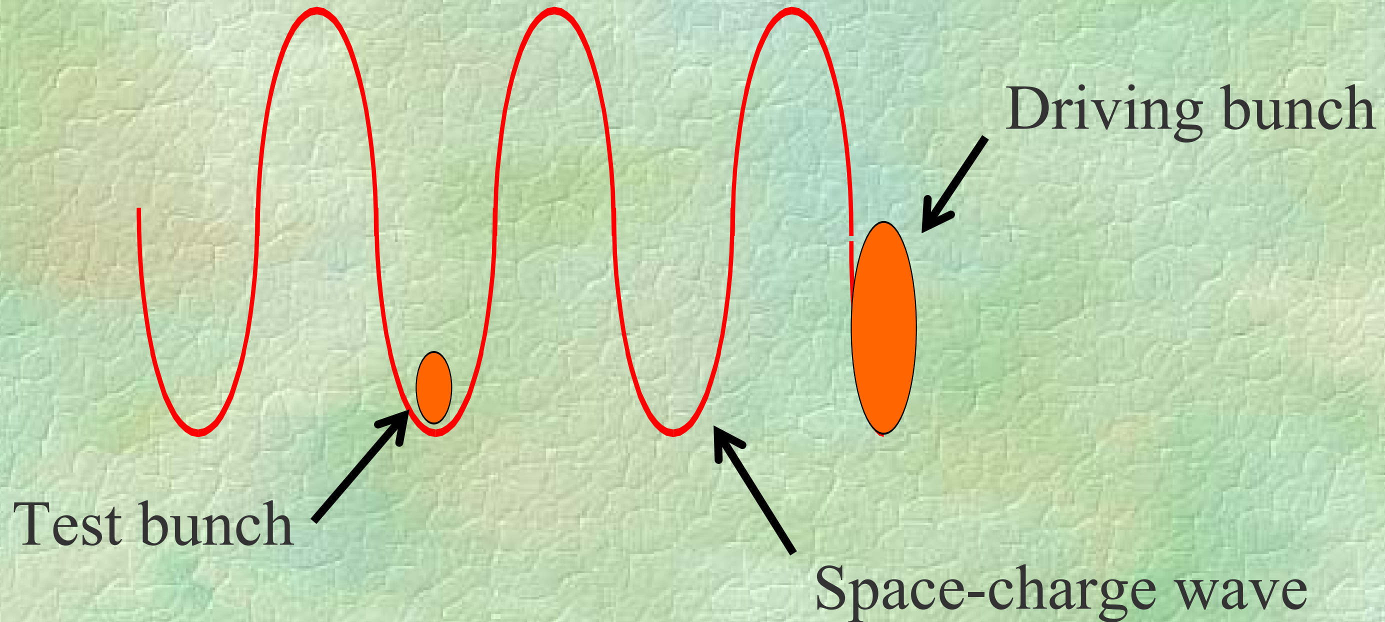




Overview

E-beam & Plasma

- *Wake-Field Acc.*



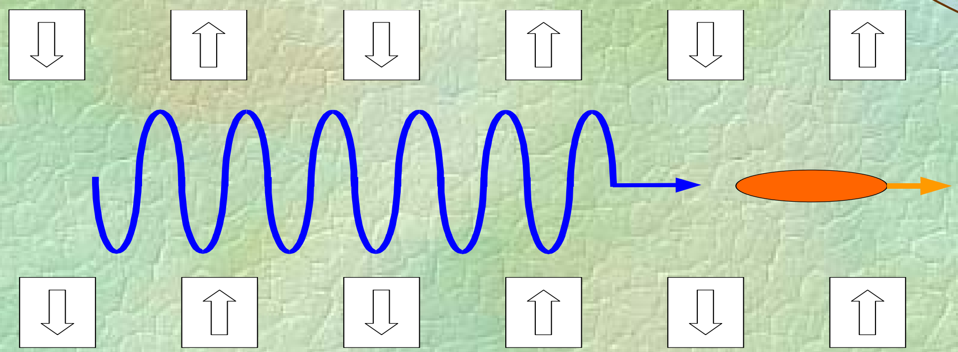
Overview

Laser & Inverse of Radiation Processes

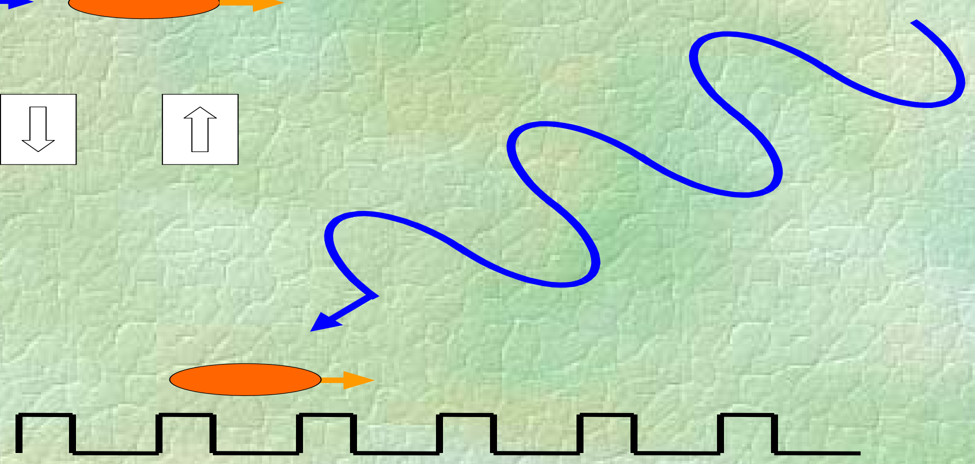
- *Inverse Cerenkov*
- *Inverse FEL*
- *Inverse Smith-Purcell*

Inverse Cerenkov

Inverse FEL



Inverse Smith-Purcell

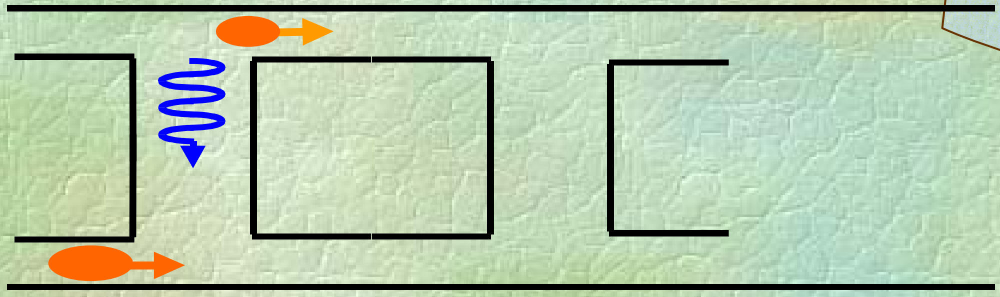


Overview

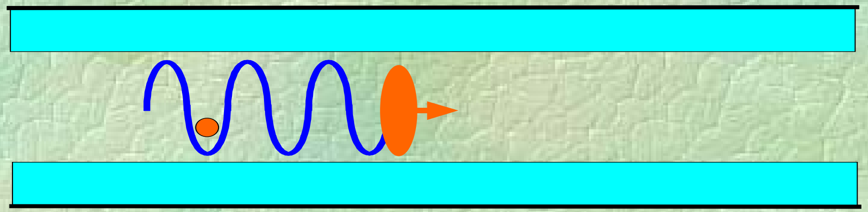
E-beam & Structure

- *Two-Beam Acc.*
- *Cerenkov Wake-Field*

Two-beam Accelerator



Cerenkov Wake-Field Accelerator



Phase velocity = velocity of driving bunch

Motivation

Laser & Plasma

- Laser Wake-Field
- Plasma Beat-Wave

Inverse Laser ?

Laser & Inverse of Radiation Processes

- Inverse Cerenkov
- Inverse FEL
- Inverse Smith-Purcell

E-beam & Plasma

- Wake-Field Acc.

Amplify a Wake ?

Amplify Cerenkov Radiation ?

E-beam & Structure

- Two-Beam Acc.
- Cerenkov Wake-Field

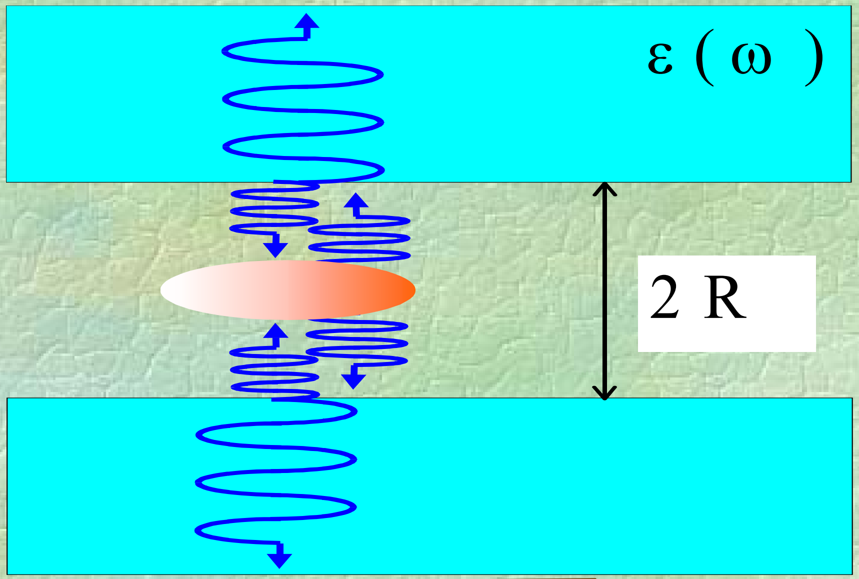
Particle Acceleration by Inverted Medium

Passive Dielectric

- *Cerenkov Radiation*
- *Decelerating Force*

Resistive Material

- *Eddy Currents*
- *Decelerating Force*



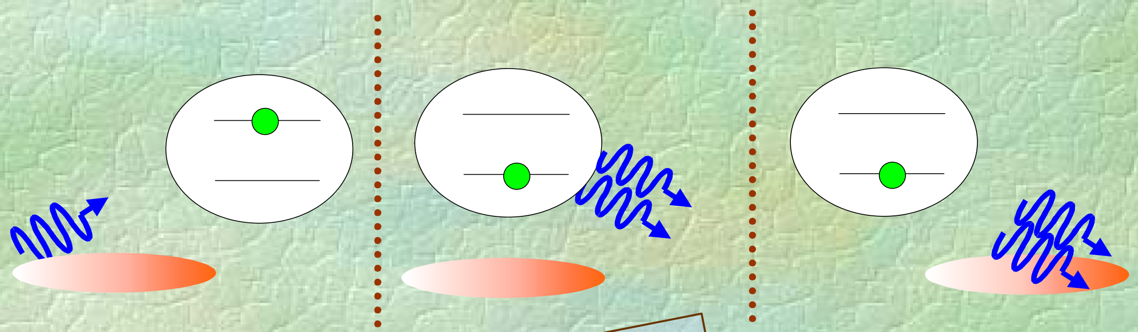
Inverted Medium

- *Negative Resistivity*
- *Induced Currents*
- *Accelerating Force*

Phys. Lett. A, 205, p.355 (1995)

PRE, **53**, p.6427 (1996).

Particle Acceleration by Active Medium



Inverse Frank-Hertz or
Collision of the Second Kind

- *Single Particle - Latyscheff(1930)*
- *Accumulative effect - yet to be demonstrated experimentally!!*

PASER:

Particle Acceleration by Stimulated Emission of Radiation

Phys. Lett. A, 205, p.355 (1995)

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Amplify a Wake ?

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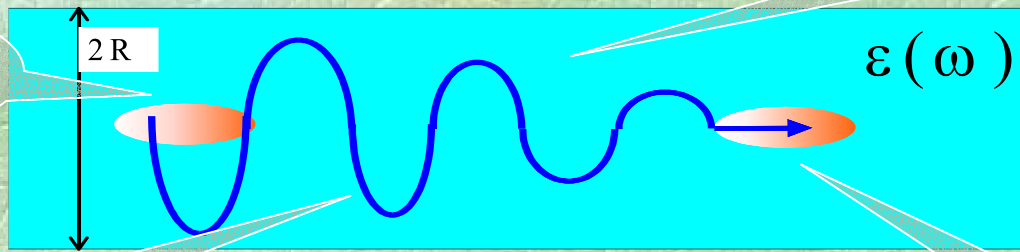
Wake-Field Amplification

Inverted medium

Accelerated bunch



Amplified wake

Trigger bunch

$$\varepsilon(\omega) = 1 + \sum_{\nu} \frac{\omega_{p,\nu}^2}{\omega_{0,\nu}^2 - \omega^2 + 2j\omega\omega_{1,\nu}} \cong \varepsilon_r + \frac{\omega_{p,n}^2}{\omega_{0,n}^2 - \omega^2 + 2j\omega\omega_{1,n}}$$

Effective dielectric coefficient

$$A_{z,s} \propto \int_{-\infty}^{\infty} d\omega \; \frac{e^{j\omega(t - z/v)}}{D(\omega)}$$

One pole corresponds to a growing wave

Wake-Field Amplification - Eigen-frequencies

The dispersion equation:

$$D(\omega) \equiv J_0\left(\frac{\omega}{c}R\sqrt{\varepsilon-\beta^{-2}}\right) + \frac{1}{\gamma\beta}\frac{\varepsilon}{\sqrt{\varepsilon-\beta^{-2}}}J_1\left(\frac{\omega}{c}R\sqrt{\varepsilon-\beta^{-2}}\right)\frac{K_0\left(\frac{\omega}{c}\frac{R}{\gamma\beta}\right)}{K_1\left(\frac{\omega}{c}\frac{R}{\gamma\beta}\right)}$$

For relativistic particles ($\gamma >> 1$) the poles are determined by

Ignore resonance

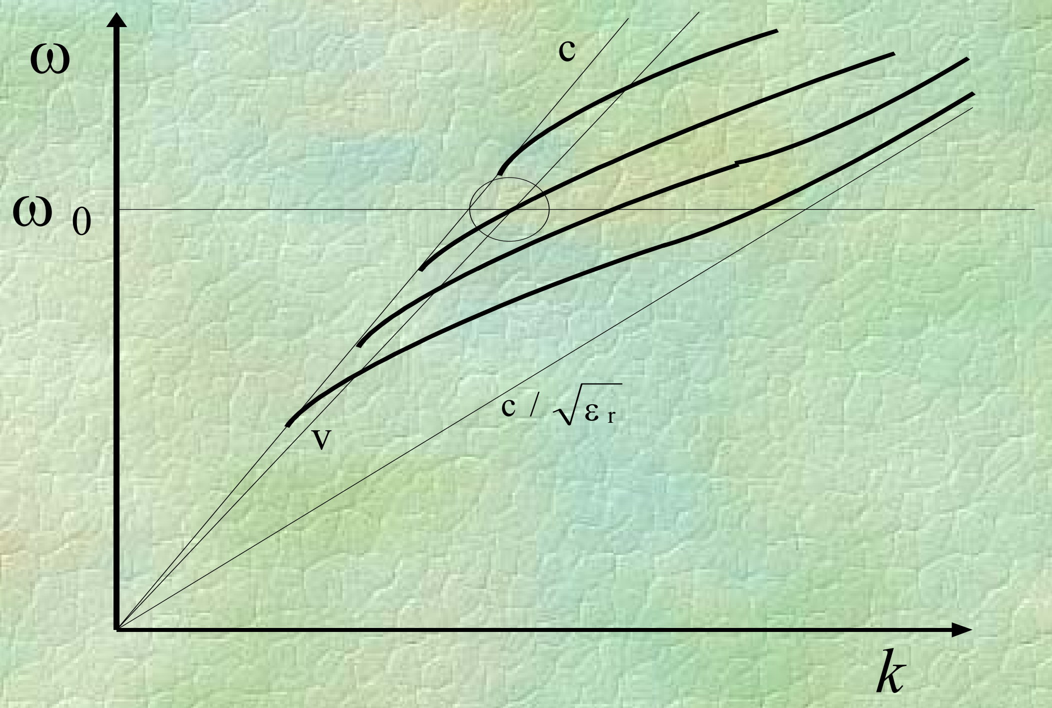
$$D(\omega) \cong J_0\left(\frac{\omega}{c}R\sqrt{\varepsilon(\omega)-1}\right) = 0 \quad \Rightarrow \quad \frac{\omega_0}{c}R\sqrt{\varepsilon_r - 1} = p$$

Resonance introduces a change:

Inversion: $\omega_p^2 < 0$

$$\omega = \omega_0 + \delta\omega \quad \Rightarrow \quad \delta\omega = \pm j\frac{|\omega_p|}{2\sqrt{\varepsilon_r - 1}}$$

Wake-Field Amplification - Dispersion Curves



Although multiple modes are possible in this geometry only a single mode will be amplified - provided the mode separation is sufficient.

Wake-Field Amplification - Gradient

Length of the driving bunch

Longitudinal component of the electric field:

$$E_z(r,z,t) \cong E_d J_0\left(p\frac{r}{R}\right) \sin[\omega_0(t-z/v)] e^{|\delta\omega|(t-z/v)}$$

Charge of the trigger bunch

$$E_d \cong \frac{q}{4\pi\varepsilon_0 \varepsilon_r R^2 J_1^2(p)} \left[\frac{J_1\left(p\frac{R_d}{R}\right)}{0.5\, p\frac{R_d}{R}}\right] \left[\frac{\sin\left(\frac{\omega_0}{v}\frac{\Delta}{2}\right)}{\frac{\omega_0}{v}\frac{\Delta}{2}}\right]$$

Radius of the driving bunch

Total power flow

Interaction Impedance

$$Z_{int} \equiv \frac{(E_z R)^2}{2P} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{\varepsilon_r - 1}{\pi J_1^2(p)} \propto \frac{\omega_0}{c} R$$

Zero of Bessel function

Wake-Field Amplification - Saturation

At high intensities the inversion is reduced by the field:

$$\delta\omega \to \delta\omega \frac{1}{1+(E/E_{cr})^2}, \qquad E_{cr} \equiv \frac{\hbar}{\mu\sqrt{\tau T_2}}$$

Dipole moment

Relaxation time constants

Consequently, at a distance *d* after the driving bunch

$$E = E_d \exp\left\{\frac{d}{c}|\delta\omega| \frac{1}{1+(E/E_{cr})^2}\right\}$$

and for a given accelerating gradient (E_{acc}) the witness bunch

$$d_w = \frac{c}{|\delta\omega|}\left[1+\left(\frac{E_{acc}}{E_{cr}}\right)^2\right]\ln\left(\frac{E_{acc}}{E_d}\right)$$

Wake-Field Amplification - Parameter Analysis

Geometric and Electrical parameters

R[cm]	= 1
D[cm]	= 100
R_d [cm]	= 0.01
Δ [cm]	= 0.1
E_{acc} [GV/m]	= 1
E_{sat} [MV/m]	= 10

Wake-Field Amplification - Parameter Analysis

	ND:YAG $[Y_3A_{L5}O_{12}]$	TI SAPPHIRE $[TI^{3+}: AL_2O_3]$
ε_r	1.82	1.76
λ [μm]	1.06	0.514
N_{dop} [atom/cm^3]	5.8×10^{19}	3.3×10^{19}
Dopant	Yttrium (1%)	Ti_2O_3 (0.1%)
p	5.362×10^4	9.981×10^4
Z_{int} [MΩ]	8.64	16.41
Energy [kJ]	3.24	3.8
N_{acc} [50% eff]	1.0×10^{13}	1.2×10^{13}
$\delta\omega/\omega_0$	0.134	0.051
E_d [V/m]	3×10^{-4}	6×10^{-5}
d_w [m]	0.36	0.49
P[MW]	5.78	3.05
S[MW/cm^2]	1.8	0.97
Gain [dB/cm]	6.9	5.4

Summary

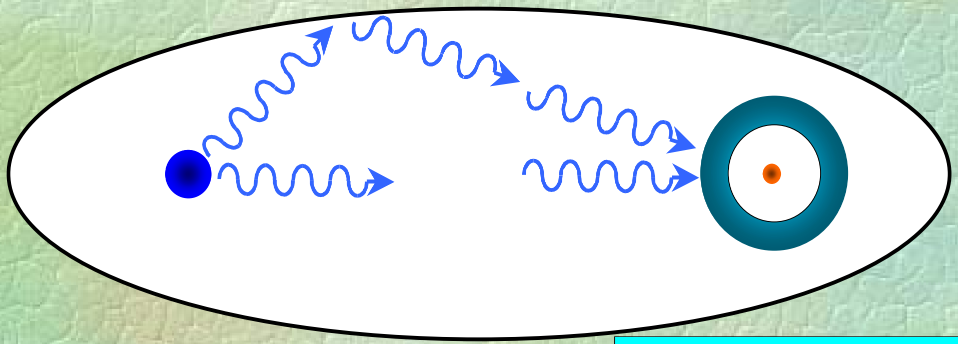
- *PASER: Electrons gain energy stored in the medium. For ``competitive`` gradients the charge density required is very high thus the alternative is*
- *Wake-Field Amplification. Energy is in the medium -- no need for optical system.*
- *Acc. mode moves at the speed of trigger bunch.*
- *Inherent longitudinal electric field.*
- *Growth controlled by the population inversion.*
- *Less than 0.1π mm-mrad emittance growth.*

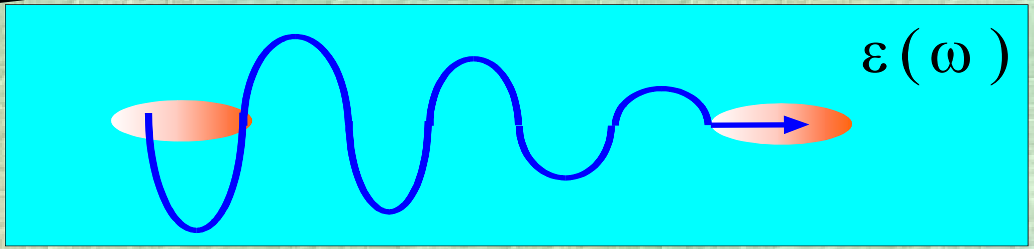
Summary

- *Vacuum acc. by combining solid-state medium.*
- *Although the transverse dimension entails many modes excitation, they all move at V_d and all oscillate at the frequency of the medium ω_0*
- *Nd: YAG and Ti: Sapphire store sufficient energy to accelerate more than 10^9 electrons - ignoring the longitudinal space-charge effect.*

Experiment Suggested at ORION

- Goal:
  - Acc. with Energy Stored in the Medium
  - Amplification of Cerenkov Radiation





- Investigate:
  - Saturation effects
  - Energy out vs. Energy stored
  - Trigger bunch effect (N_d, γ_d, energy spread)
  - Transition radiation effect.