The Abdus Salam International Centre for Theoretical Physics

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CIMPA/ICTP Geometric Structures and Theory of Control

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Intense Laser- Matter Interaction: Some Basics

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ICTP-IAEA College on Plasma Physics October 2012
Lectures by G. Ravindra Kumar, TIFR Mumbai

1. Intense Laser- Matter Interaction: Some Basics [mainly for ultrashort (femtosecond) pulses]

2. High energy density science (HEDS) experiments with table top terawatt lasers: the why and how

3. Physics issues and challenges in HEDS with table top lasers: some examples

Intense Laser- Matter Interaction- Some Basics

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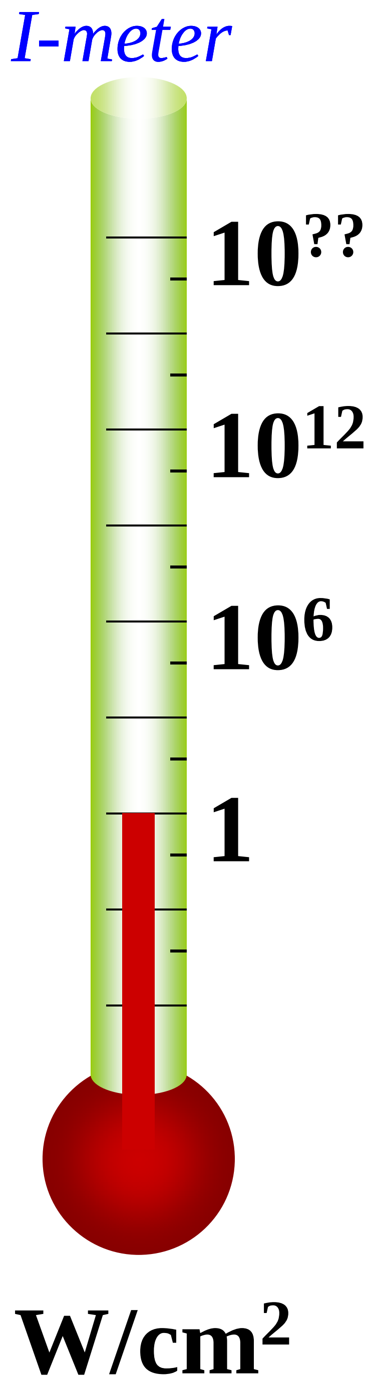
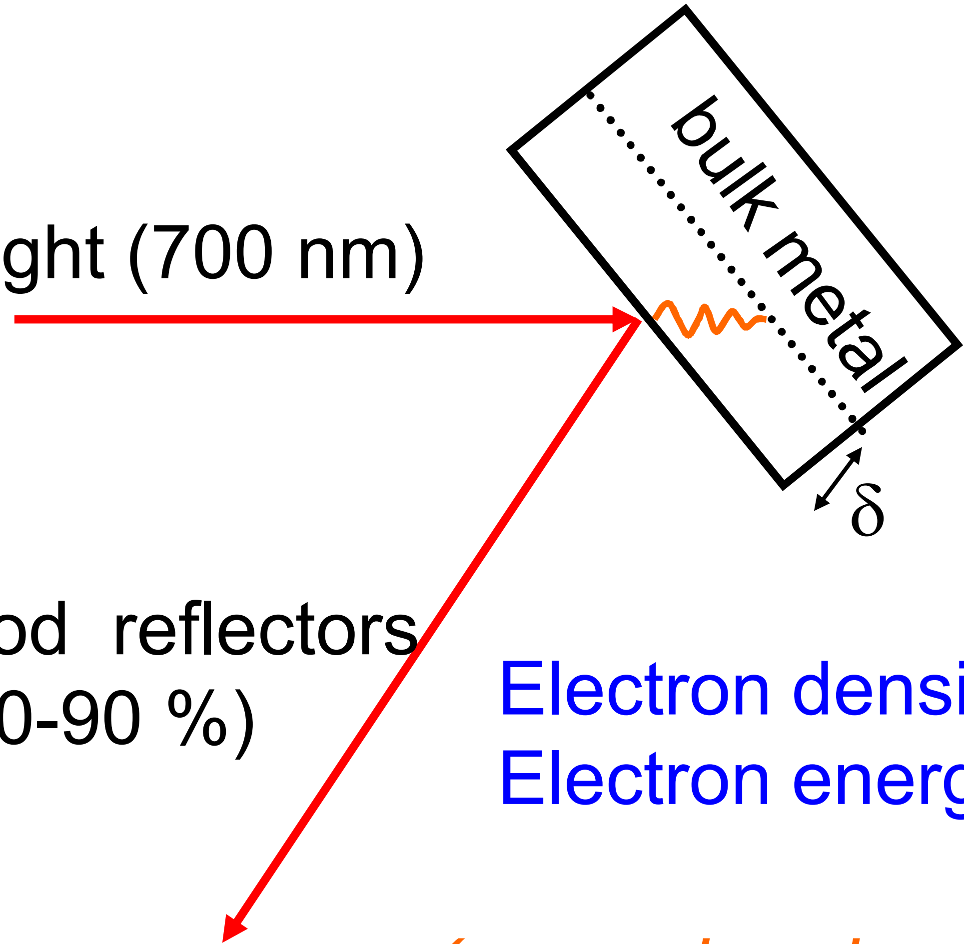
Normal Light – Matter interaction


I-meter
10??
10^12
10^6
1
W/cm^2

A Useful Example From Normal Optics
Reflection From a Metal

Visible light (700 nm)



Metals - good reflectors
(80-90 %)

700 nm

Drude model

δ - skin depth

$= 1/(2\pi\mu\sigma\omega)^{1/2}$

(10-50 nm)

Electron density - 10^{23} cm^{-3}
Electron energy (typ.)- 10^{-3} eV

(remember these numbers)

Metals – why do they reflect light?

Metals have a free electron `plasma' inside.
The electrons get excited by light irradiation

Collective motion

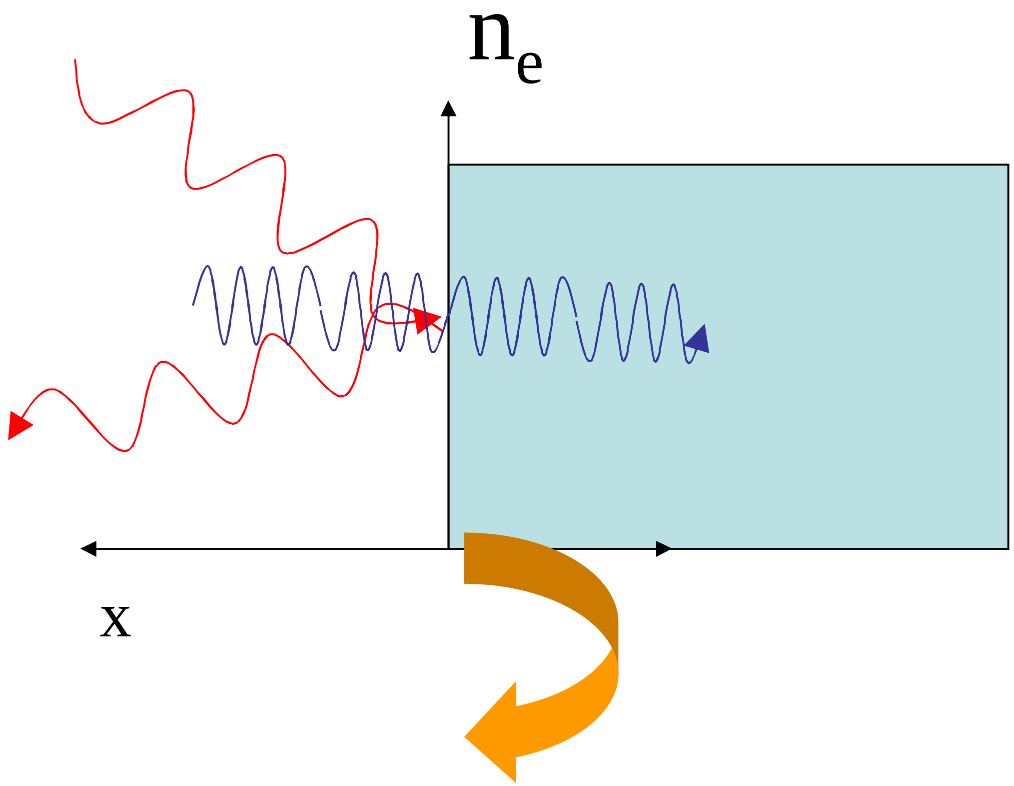
Dielectric Function $$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\eta)}$$

Plasma frequency $\omega_p = 4\pi Ne^2/m_e$ (`Plasmon', collective mode)
η- collision frequency, m_e - electron mass, N - electron density

If incident $\omega < \omega_p$ light gets reflected. **`Critical Layer'**
(another ex:Radio wave communication)

If incident $\omega > \omega_p$ light can walk through.

Metals have step-like electron density profiles

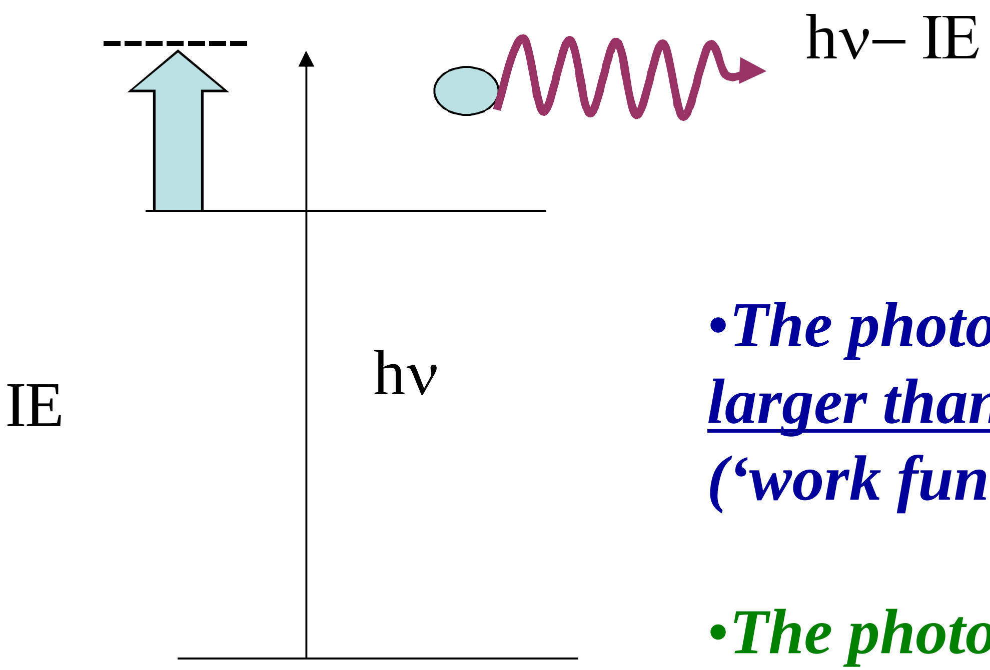


n_{critical} (red)

Note: the density profile is fixed

The photoelectric effect

……………..*as every one knows it*



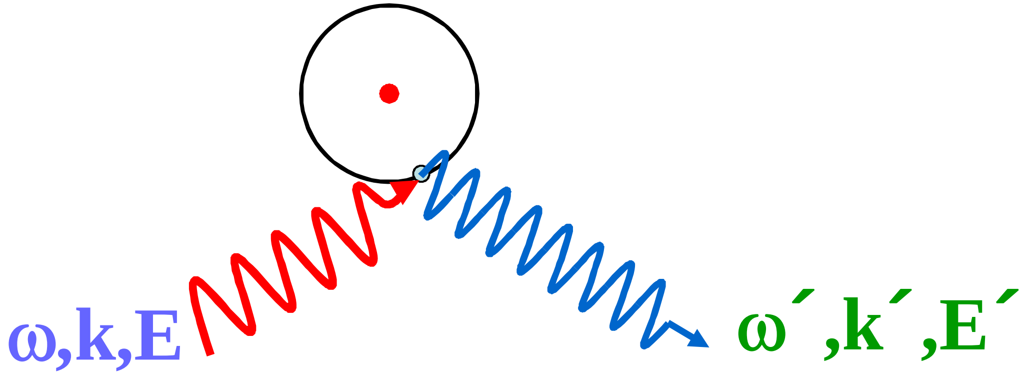
- ***The photon energy has to be equal to or <u>larger than</u> ionization energy ('work function')***

- ***The photon flux (intensity) <u>does not play a role</u>***

LIGHT-MATTER INTERACTION

Essentially Induced Dipole Reradiation

(electronic response)



E small

(Linear Optics)

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

$$\nabla^2 \mathbf{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2}$$

Electron oscillates in simple harmonic fashion

A lady intervenes………….

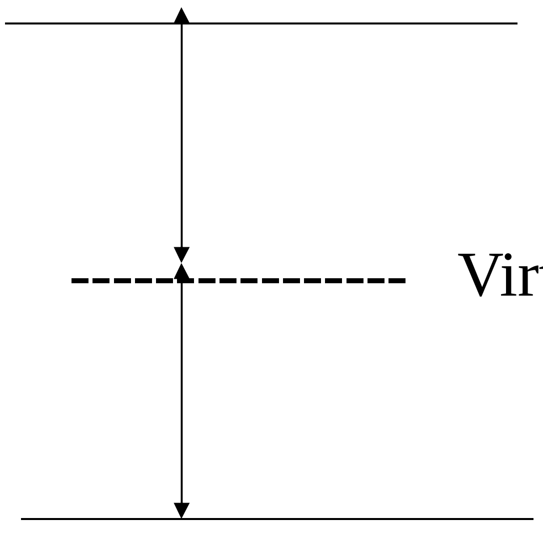
and changes things forever !

For her dissertation (1930), she calculated the probability that ***an electron orbiting an atom's nucleus would emit two photons of light as it jumped to an orbit closer to the nucleus***. Her challenging calculation was confirmed experimentally in the 1960s.

Maria Goeppert Mayer (Nobel prize in 1963)

Ann. Physik 9 (1931) 273

Perturbative calculation at `high' intensities



$|f\rangle$

Virtual level $|k\rangle$

$|i\rangle$

$$A_{if} = CI^{2} \sum \frac{(R_{i,k} R_{k,f})^{2}}{(\omega - \omega_{i,k})^{2}}$$

I- input light intensity, $R_{i,k}$ – matrix elements

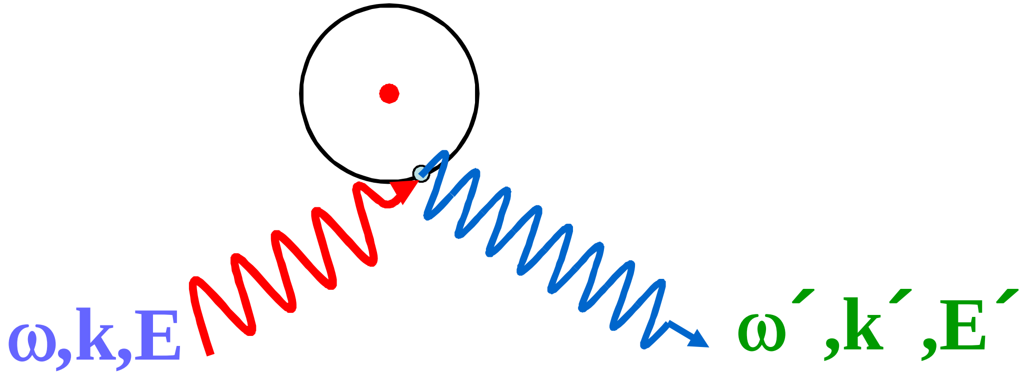
The ‘Multiphoton’ notion

- Basic idea- high photon fluxes imply a large probability of for two or more photons to interact simultaneously with an atom

LIGHT-MATTER INTERACTION

Essentially Induced Dipole Reradiation

(electronic response)



E small

(Linear Optics)

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E} + \varepsilon_0 \chi^{(2)} \mathbf{E}^2 + \varepsilon_0 \chi^{(3)} \mathbf{E}^3 + \ldots$$

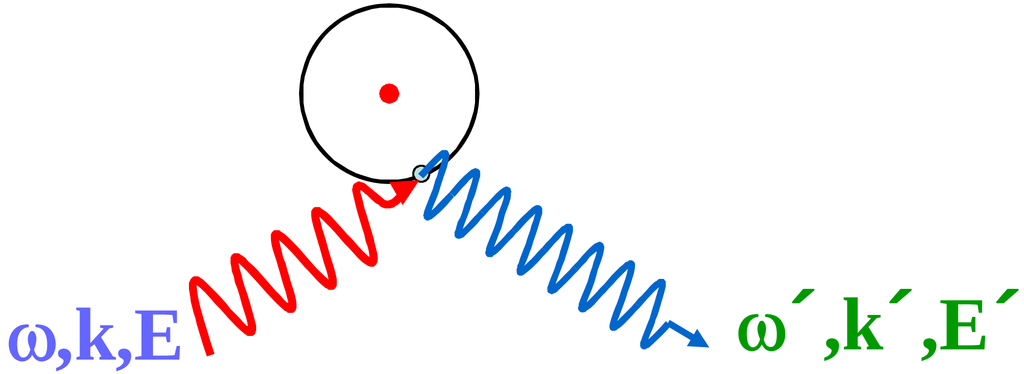
$$\nabla^2 \mathbf{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2}$$

Electron oscillates in simple harmonic fashion

Large amplitude motion - anharmonic oscillations

LIGHT-MATTER INTERACTION

Essentially Induced Dipole Reradiation (electronic response)



E large (Strong Fields)

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

$$\nabla^2 \mathbf{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2}$$

Electron oscillates in simple harmonic fashion

Large amplitude motion - anharmonic oscillations

What happens if we peak up the intensities further?

(and how do we do that?)

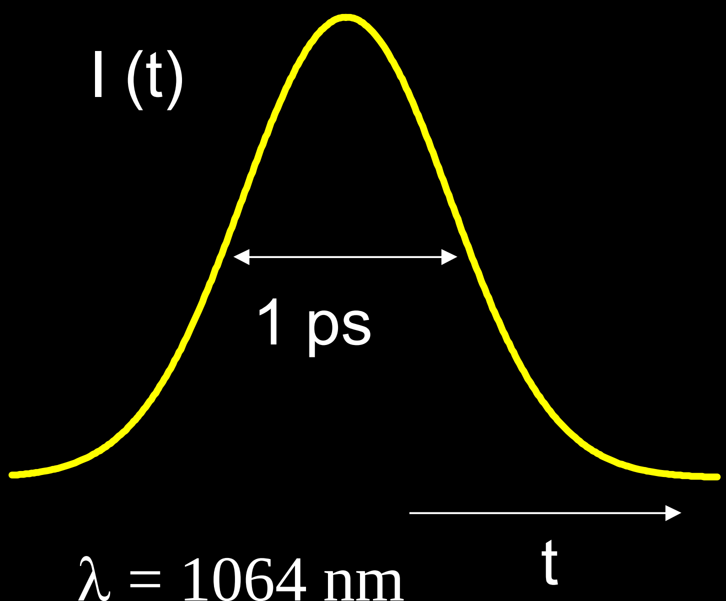
By shrinking the light into ever shorter pulses ('fewer' moments) and focusing it to small sizes

The laser `*projectile*' -
`Pulse' the light to produce 'Peak' power

Peak power=

Pulse Energy / pulsing time

An ultrashort pulse



λ = 1064 nm

For the same energy- the shorter the pulse, the larger the Peak power !

1 Joule in 1 sec = 1 Watt

1 J in 1 picosecond (10^{-12} sec)

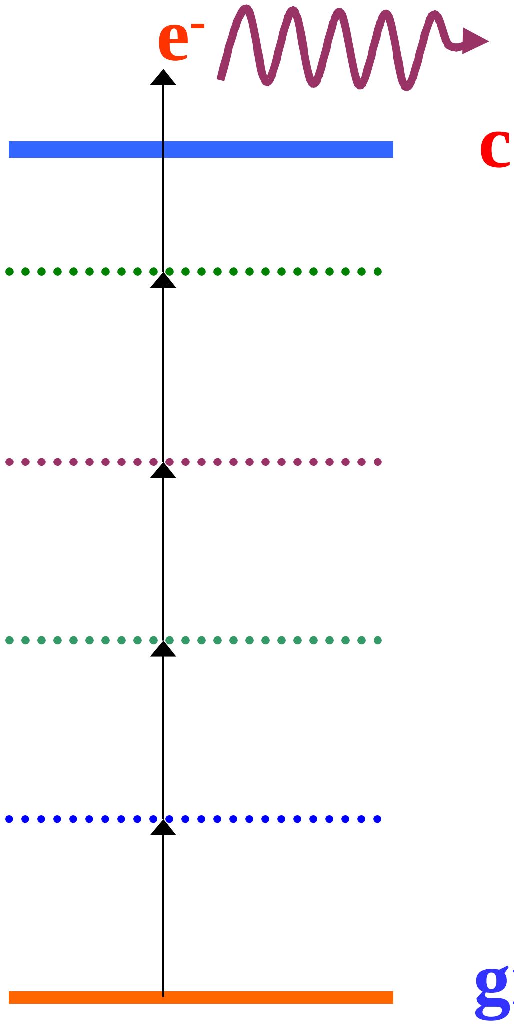
= 1 Terawatt (10^{12} W)

Photon energy

~ 1 **eV**

Multiphoton Ionization

single atom



continuum

ground state

$$R_n = \sigma_n I^n$$

Relatively low intensities
and
short wavelengths

Wavelength still meaningful

High Intensity Photoelectric effect

Breakdown of the ‘Multiphoton’ notion

If E – Electric field in the Laser Light

Δ – Detuning from Resonance $(\omega_0 - N\omega)$

μ – Transition Dipole

then

$$R_N = \text{Const}\left(\frac{\mu E}{\hbar \Delta}\right)^{2N}$$

If $\dfrac{\mu E}{\hbar \Delta} \to 1$, Perturbation Theory Breaks Down.

$\mu \sim 3 e a_0$ (a_0 – Bohr Radius)

For $\hbar \Delta \sim 1$ eV,

$$\frac{\mu E}{\hbar \Delta} \to 1$$

for

E Corresponding to $\boxed{I \approx 10^{12}\ W/cm^2}$

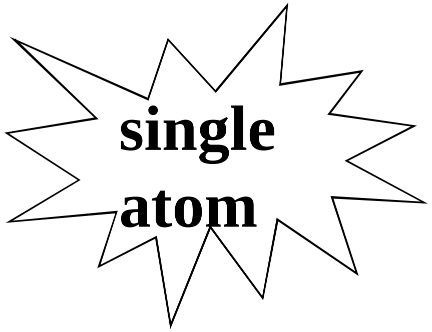
Tunnel ionization

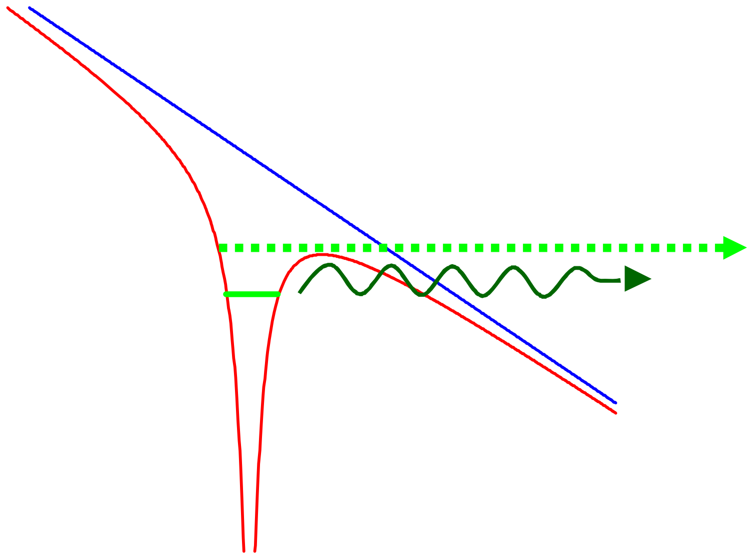
Oppenheimer (1928)
Keldysh (1965)

Nonperturbative regime - tunnel/over the barrier ionization

High intensity **Long wavelength**

$$V = -\frac{q}{x} - E.x$$





Large fields - `E´ is all that matters

What are Intense Fields ?

Extremely large E fields generated by short pulse high energy lasers

Two criteria

1. Comparison with the intra-matter Coulomb field

Hydrogen atom - 1s electron

E ~ 10^9 V/cm → Intensity $I = 2\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} |\mathbf{E}|^2 \cong 10^{16} W/cm^2$

2. Breakdown of Perturbation Approach (Polarization)

occurs at 10^{12} W/cm^2

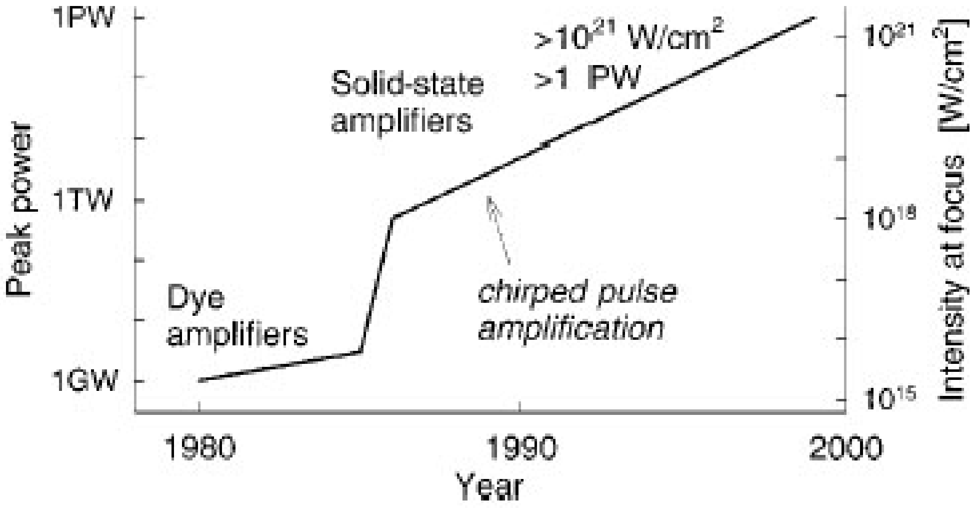
Strong < 10^{12} W/cm^2 Intense > 10^{12} W/cm^2

Super-intense >10^{16} W/cm^2

Current Highest Intensity - 10^{22} W/ cm^2 !

The LaseRevolution

Small step

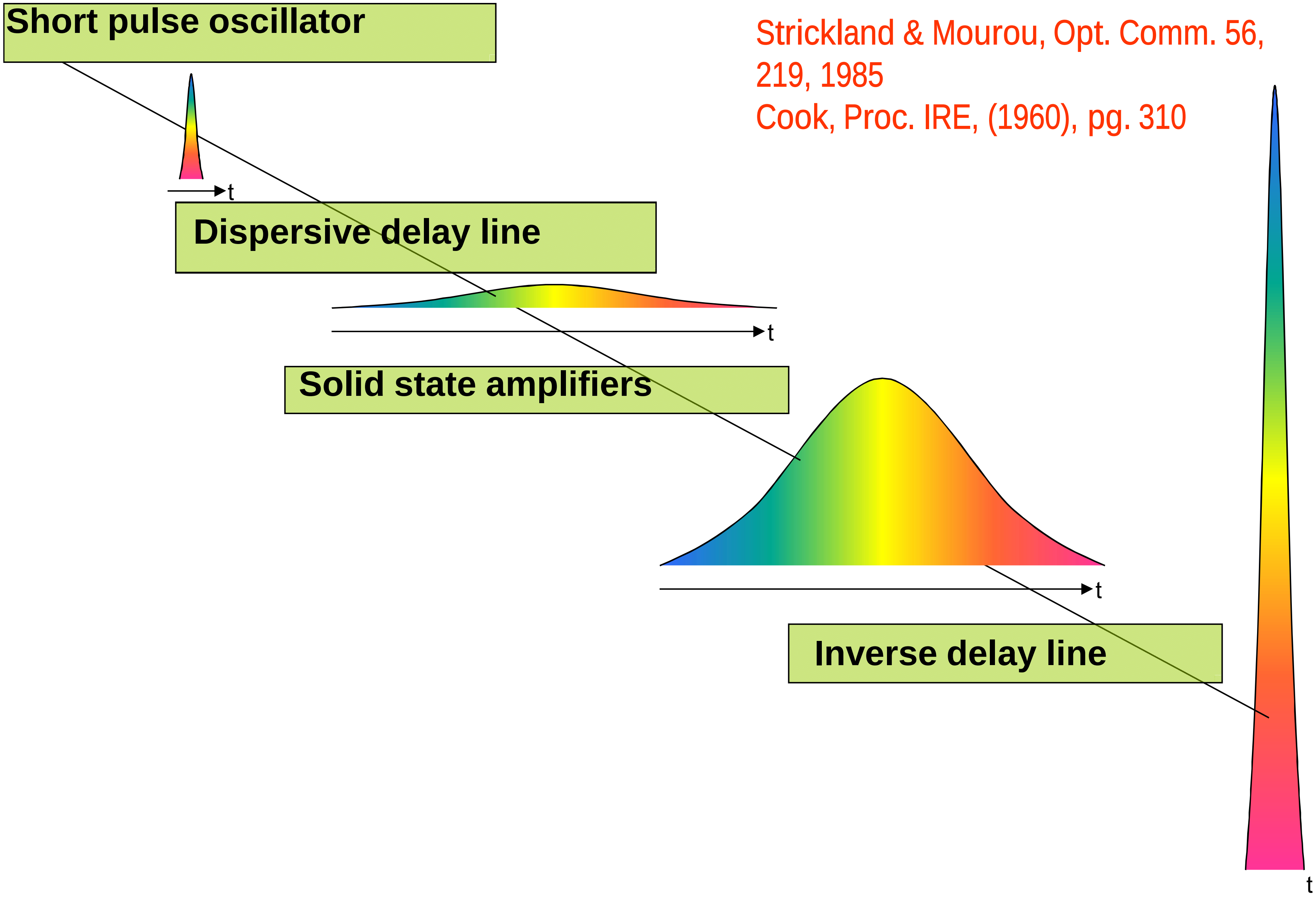


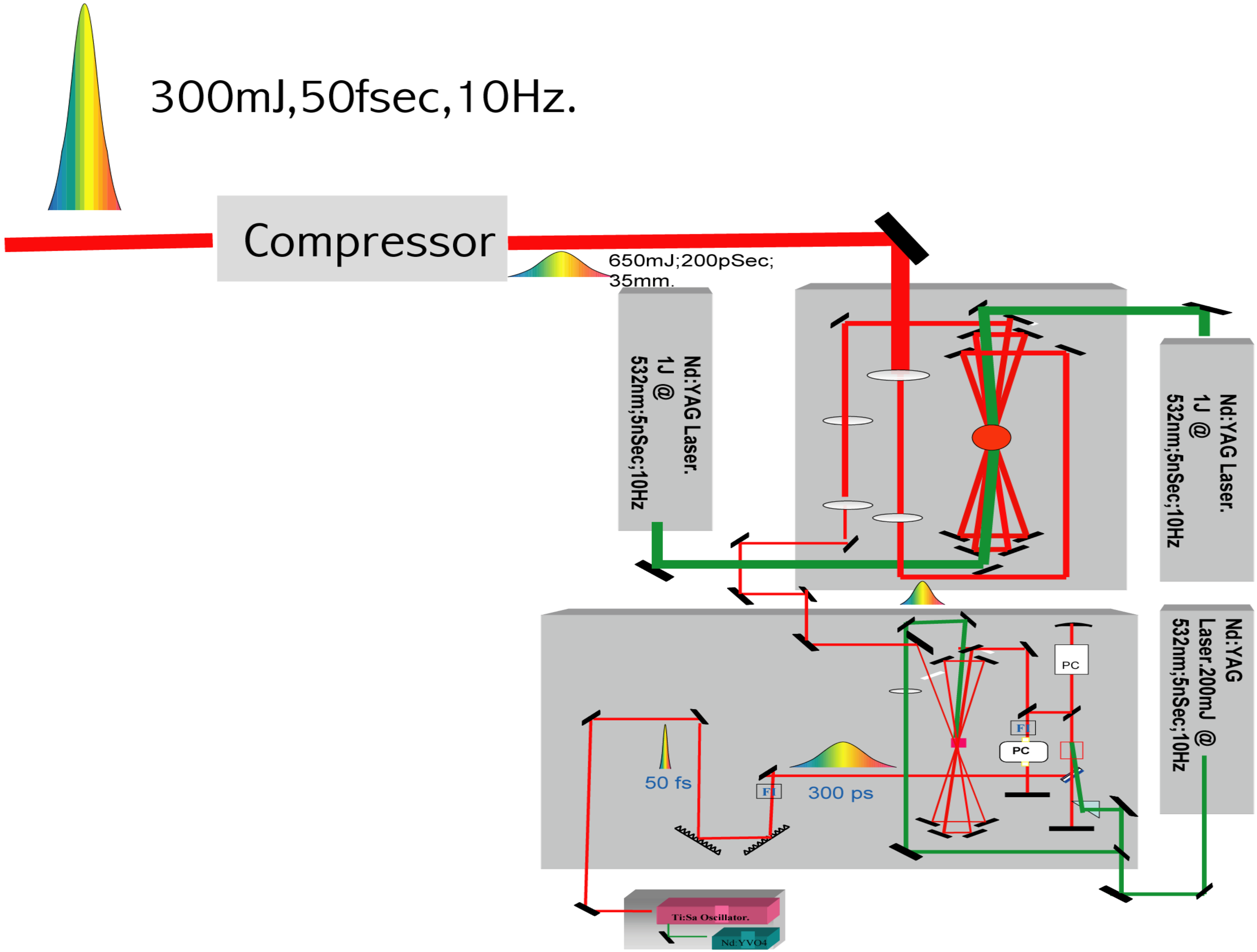
Giant Leap!

Bringing the stars down to earth!!

Chirped Pulse Amplification

Strickland & Mourou, Opt. Comm. 56, 219, 1985
Cook, Proc. IRE, (1960), pg. 310





300mJ,50fsec,10Hz.
Compressor
650mJ;200pSec;
35mm.
Nd:YAG Laser.
1J @
532nm;5nSec;10Hz
Nd:YAG Laser.
1J @
532nm;5nSec;10Hz
Nd:YAG
Laser.200mJ @
532nm;5nSec;10Hz
PC
PC
FI
FI
50 fs
300 ps
Ti:Sa Oscillator.
Nd:YVO4

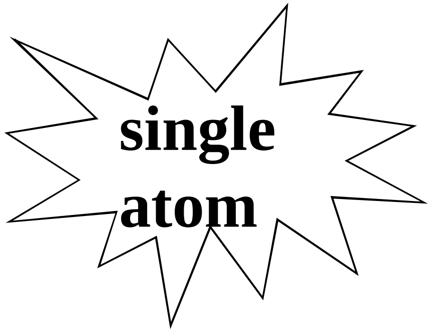
Tunnel ionization

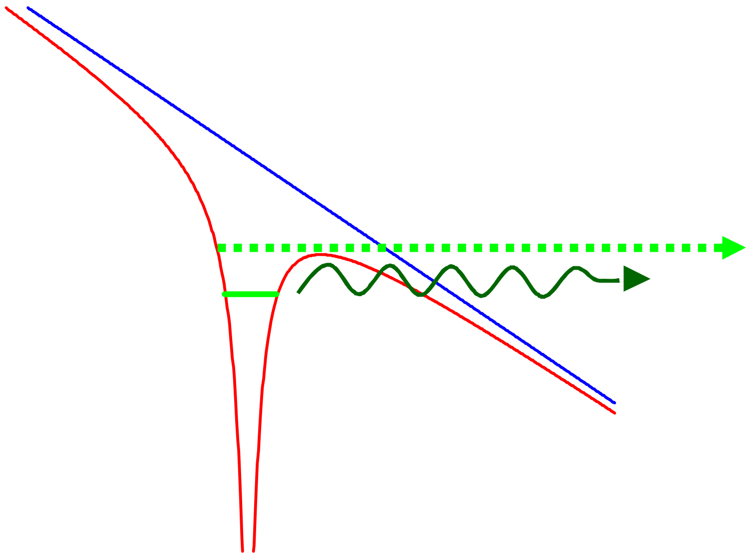
Oppenheimer (1928)
Keldysh (1965)

Nonperturbative regime - tunnel/over the barrier ionization

High intensity **Long wavelength**

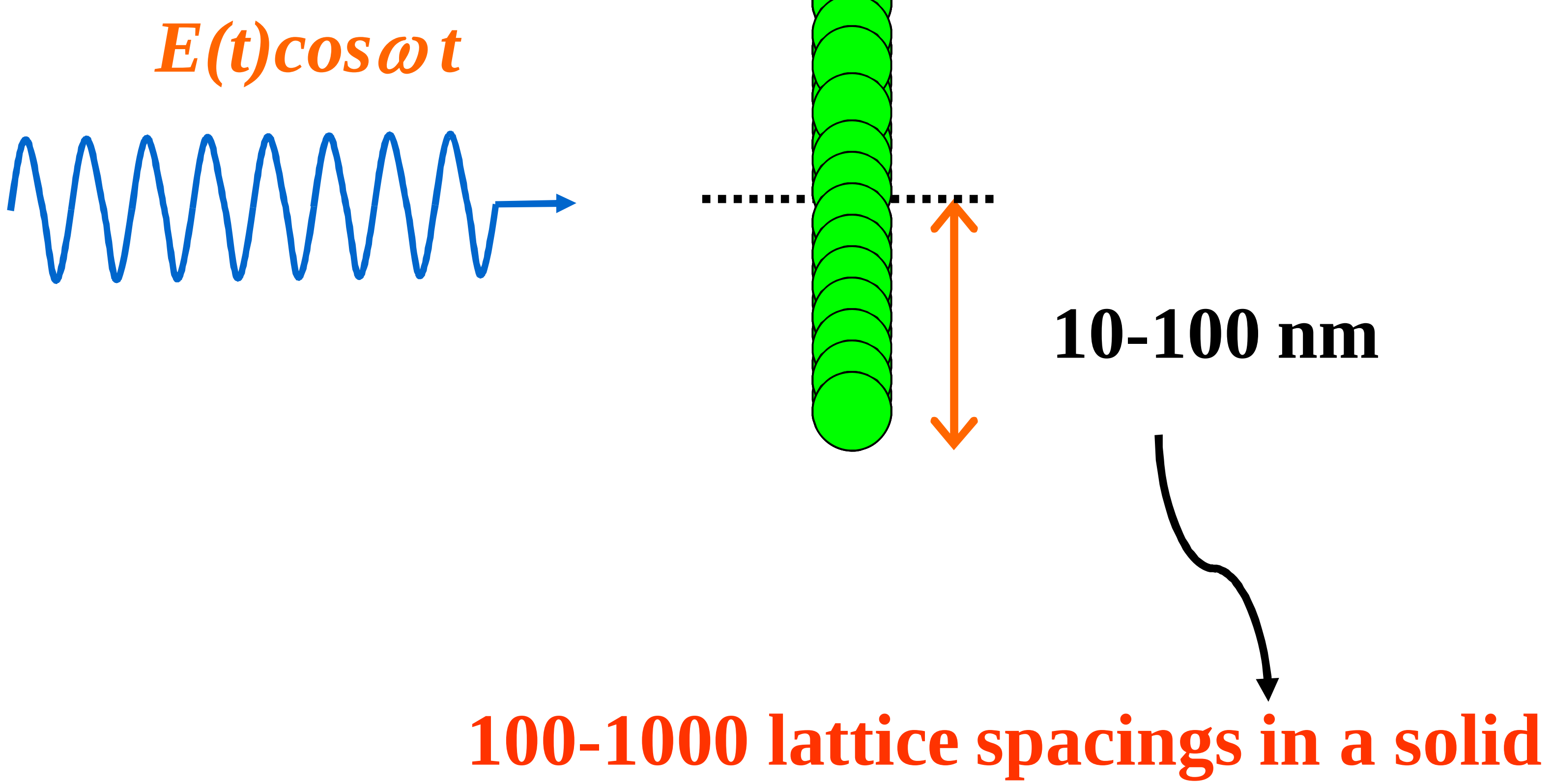
$$V = -\frac{q}{x} - E.x$$





Large fields - `E´ is all that matters

Light oscillates electrons !



Ponderomotive energy

Acceleration of the ionized electron in the laser field

$$U_P = \frac{e^2 E^2 \lambda^2}{16\pi^2 m_e}$$

e **- electronic charge**

E **- electric field in the light wave**

λ - wavelength of the laser

m_e - electronic mass

Acceleration
10^{17} g !!!

E = 2.75 X 10^8 V/cm (10^{13} W/cm^2)

U_P = 1.1 eV for λ = 1.06μm

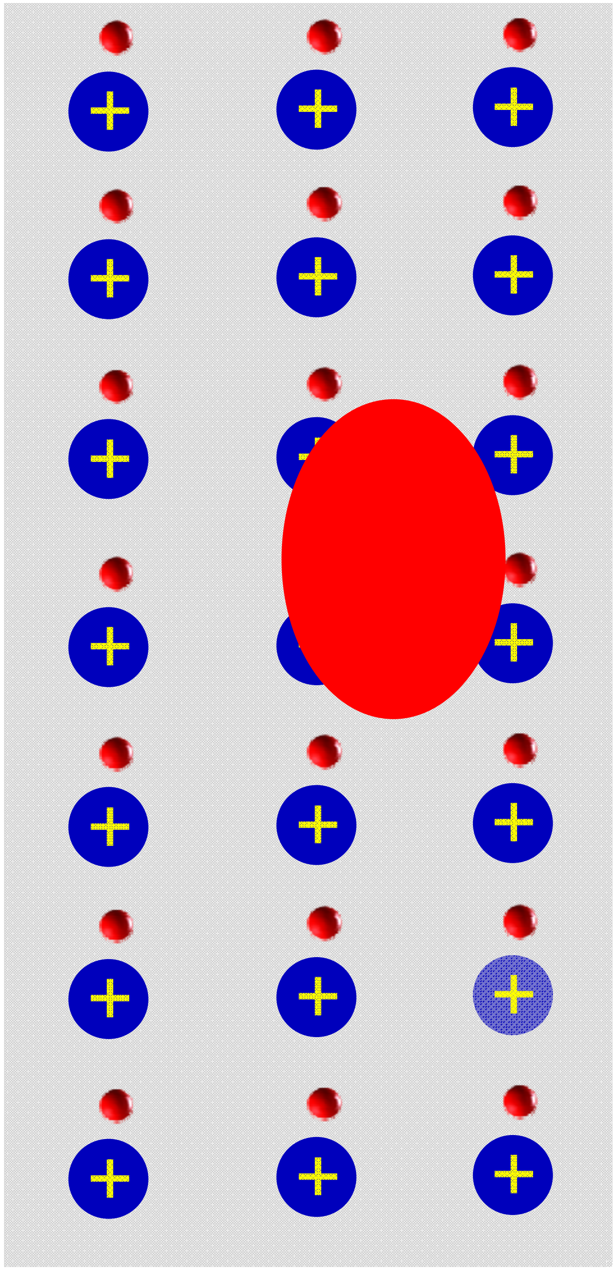
> 100 eV for λ = 10.6 μm

Relativistic

U_P > 10^6 eV for λ = 1.06μm & 10^{19} W/cm^2

Each electron interacts with 10^6 photons !!

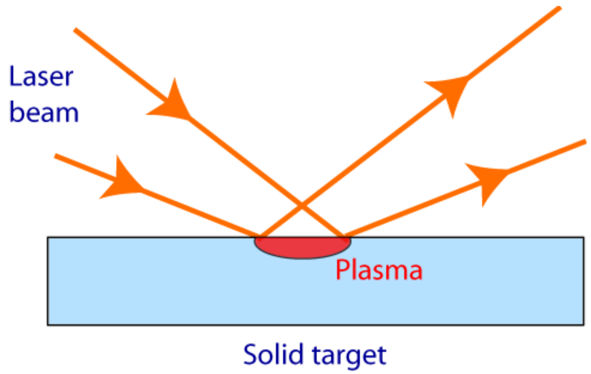
Light Ionizes a Solid

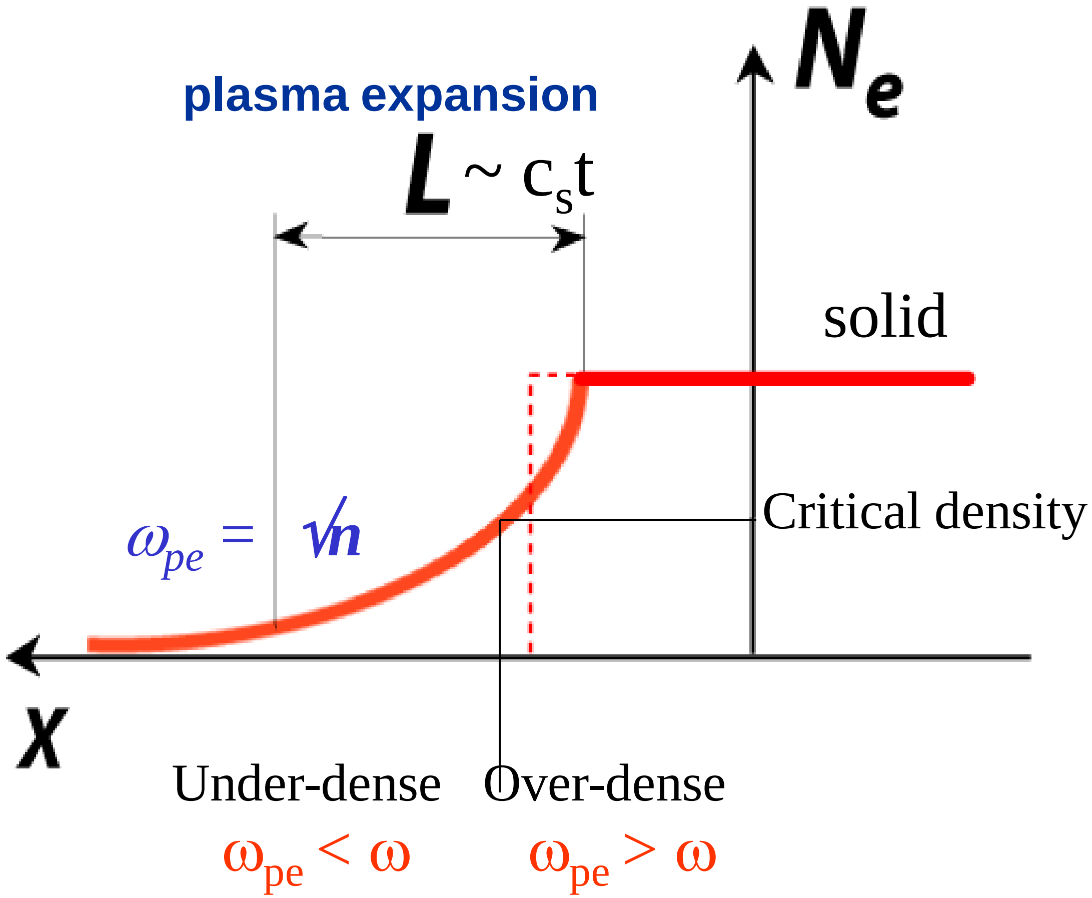


10^{23}/cc free electrons

10-100 eV

Light Absorption by Plasma

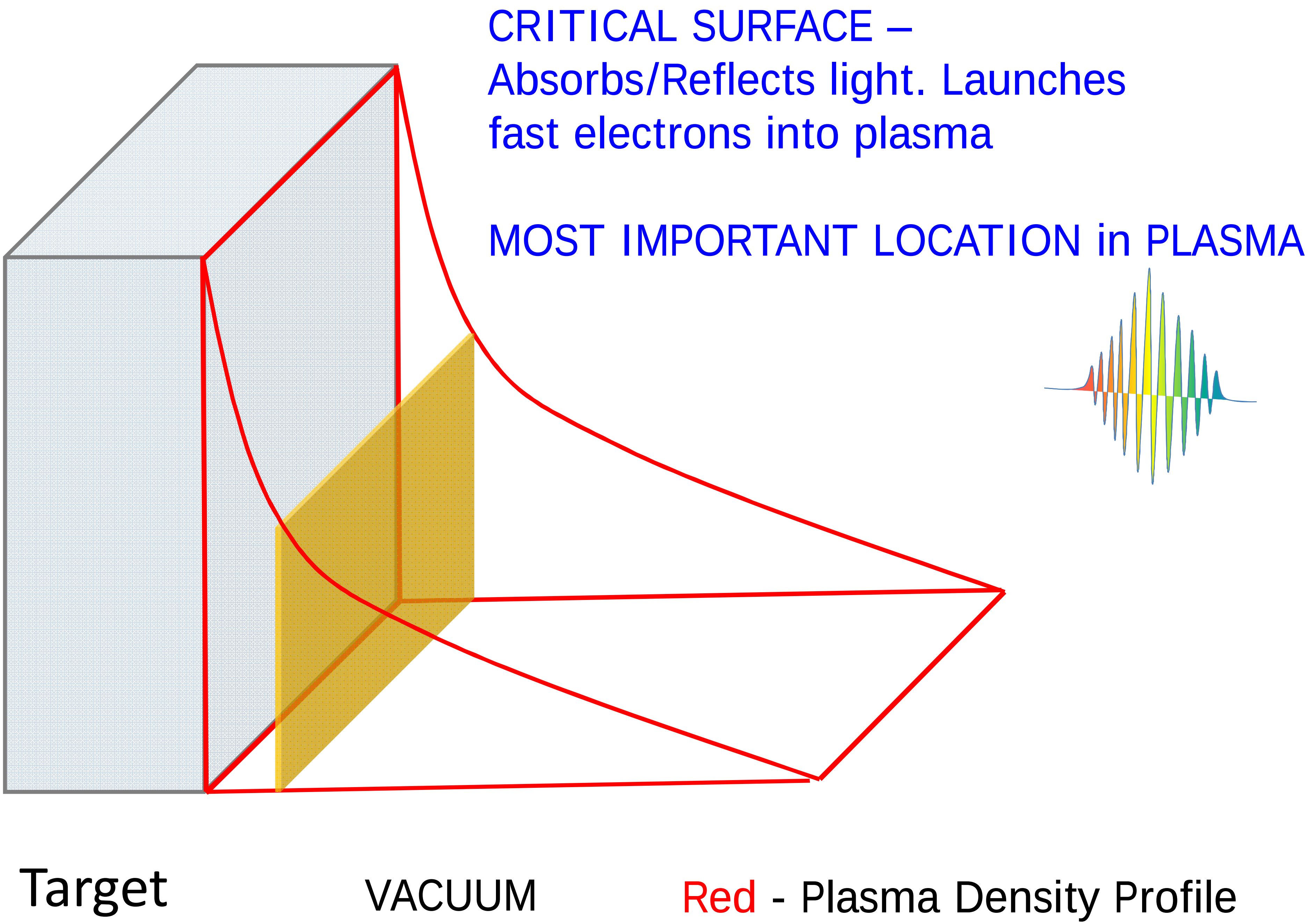




$$\varepsilon = n^2 = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)}$$

Critical at $\omega_{pe} = \boldsymbol{\omega}$

Laser Turning point; $n_{cr} \sim 10^{21} cm^{-3}$


CRITICAL SURFACE –
Absorbs/Reflects light. Launches
fast electrons into plasma
MOST IMPORTANT LOCATION in PLASMA
Target
VACUUM
Red - Plasma Density Profile

Polarization Independent Mechanism

Collisional absorption (inverse bremsstrahlung)

- electron transfers energy to other particles via collisions
- electron repeatedly gains energy from the laser field
- responsible for the 'bulk temperature' of the plasma
- the fraction of energy absorbed for a linear density profile is

$$f_A = 1 - \exp(-\frac{32\nu_{ei}^{*} L}{15c}\cos^5\theta)$$

L – plasma length

ν^* – $\nu_{ei}(n_{cr}/n_e)$, the e^--i collisional frequency

$$\nu_{ei} \propto \frac{n_e Z}{T_e^{3/2}}$$

- since $T_e \sim I^{2/3}$, collisional absorption is important only in the low intensity regime (< 10^{14} W cm^{-2})

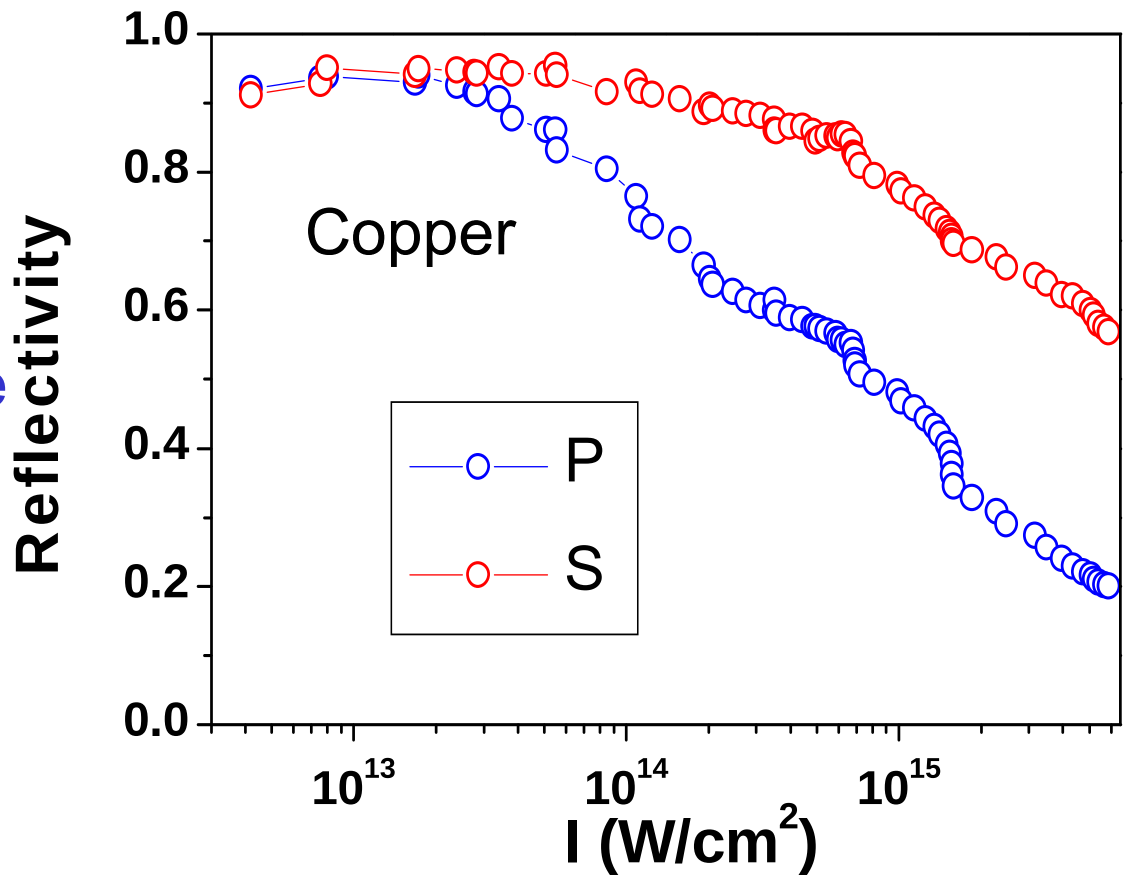
Plasma absorption

- A = 1-R

$I < 3 \times 10^{13}$ W cm^{-2}, A is almost polarization independent & obeys Fresnel laws, as IB is dominant

- at higher intensities, there is a clear polarization dependence of absorption

- the difference in absorption should account for extra absorption mechanisms, which are polarization dependent



R vs I at 45º

TIFR data

POLARIZATION DEPENDENT mechanisms

Resonance Absorption (> $\mathbf{10^{15}}$ W cm^{-2})

P-polarized light at oblique angle of incidence, exciting a plasma wave**.**

↓

'Hot' electrons

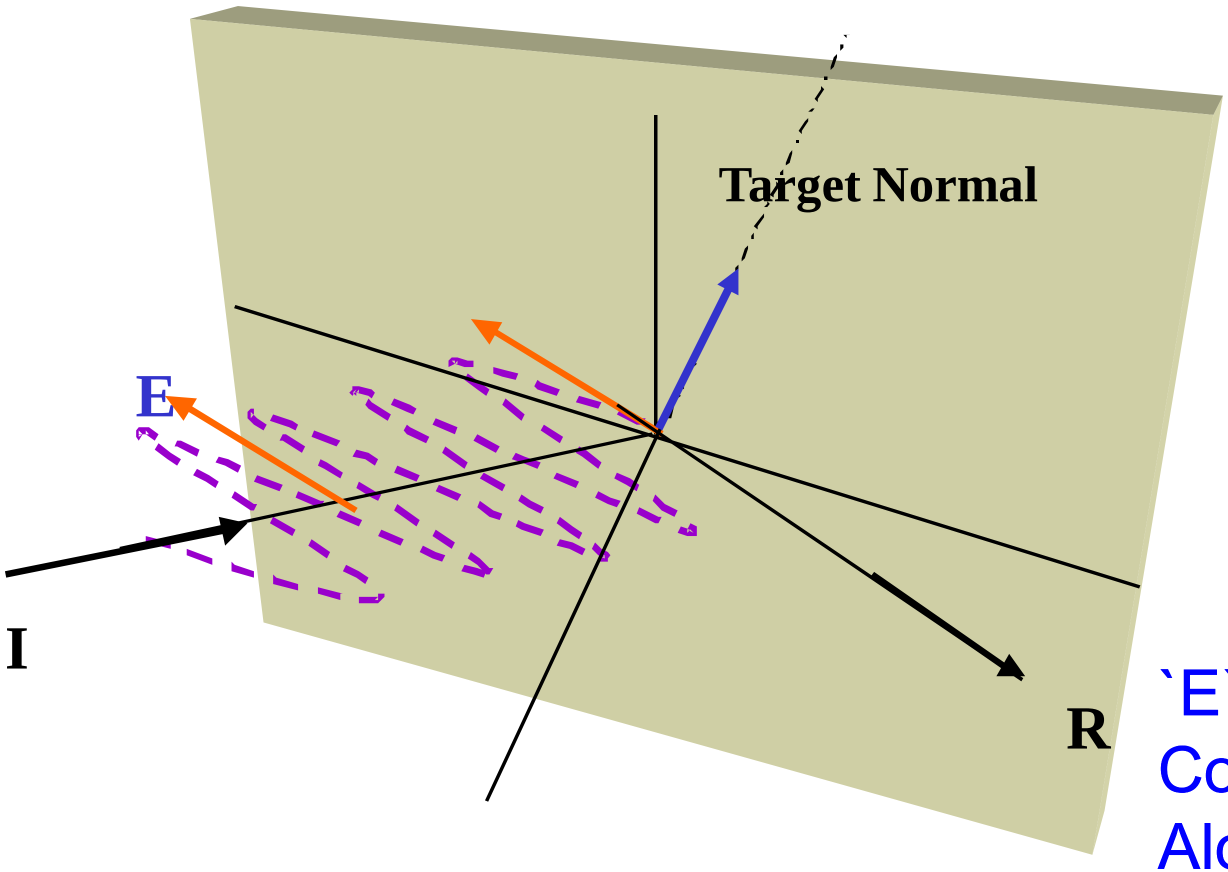
WHY study Hot electrons?

Important for Fast Ignition Fusion

Emitters of very hard X-ray pulses

Mechanism of Resonance Absorption

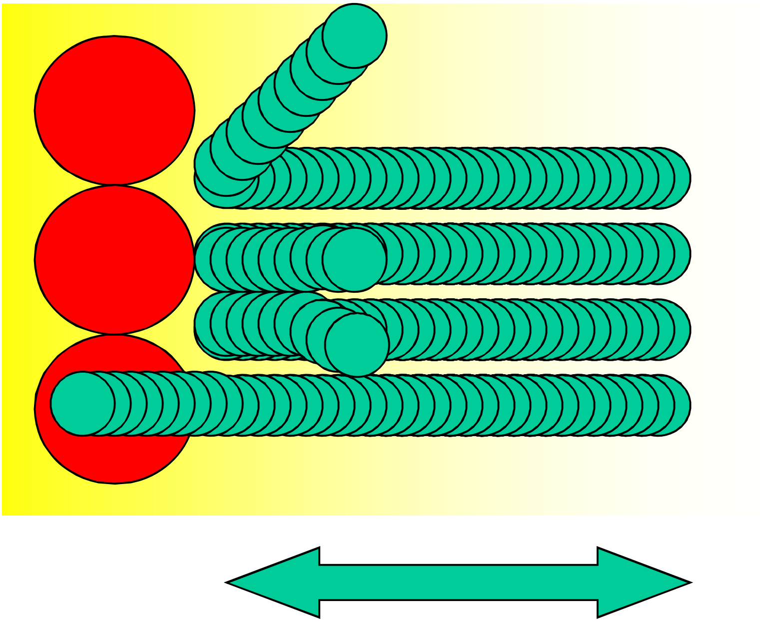
P-polarized light, Oblique incidence



Note:
\`E\` has
Component
Along normal

Resonance absorption
(only for p-polarized light)

Electron waves and wave-breaking along the density gradient

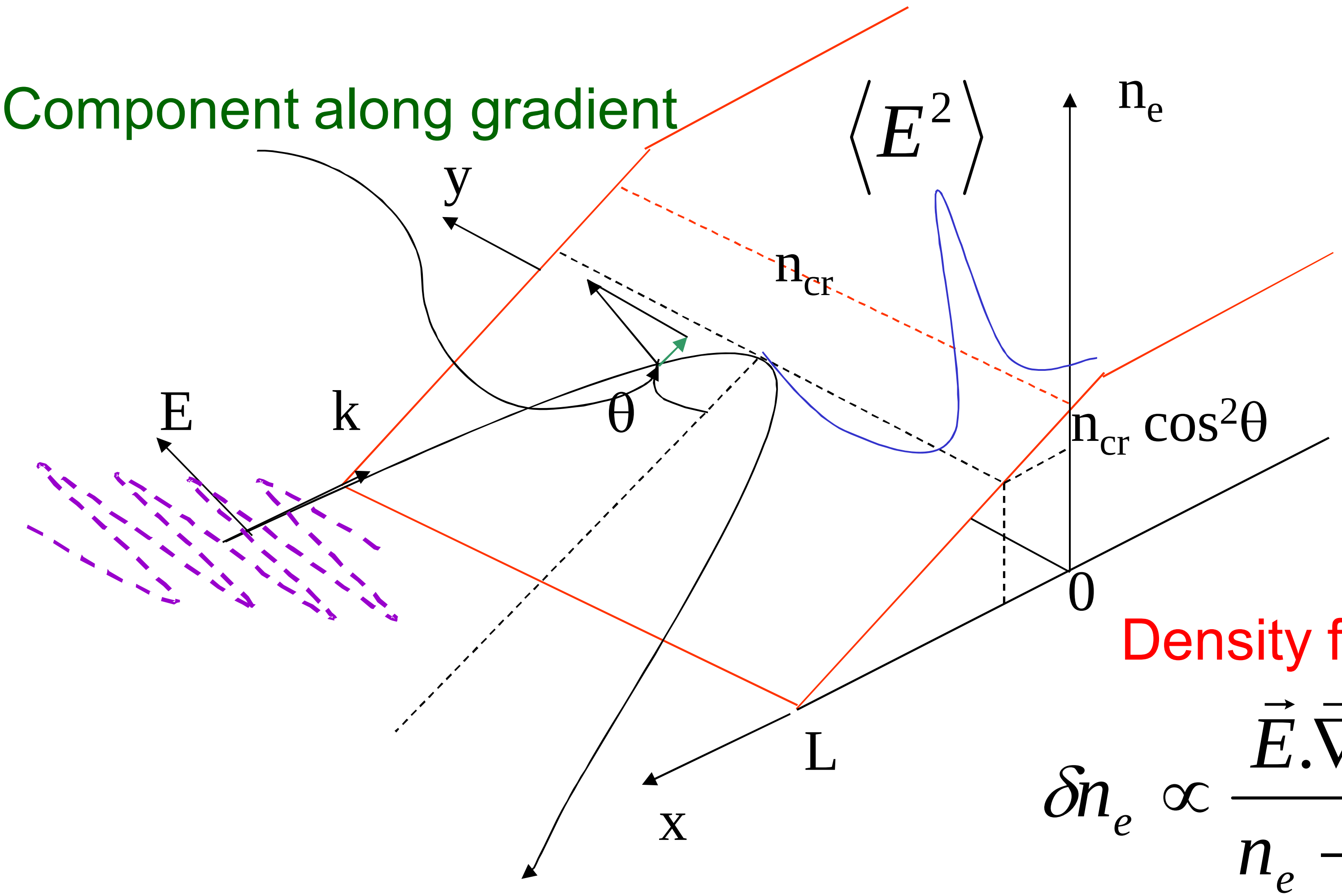


- energy absorption via damping and wave-breaking
- hot electron current (jets?)

Quiver amplitude = $\dfrac{eE}{m\omega^2}$

Large electric fields
Large density

Resonance absorption



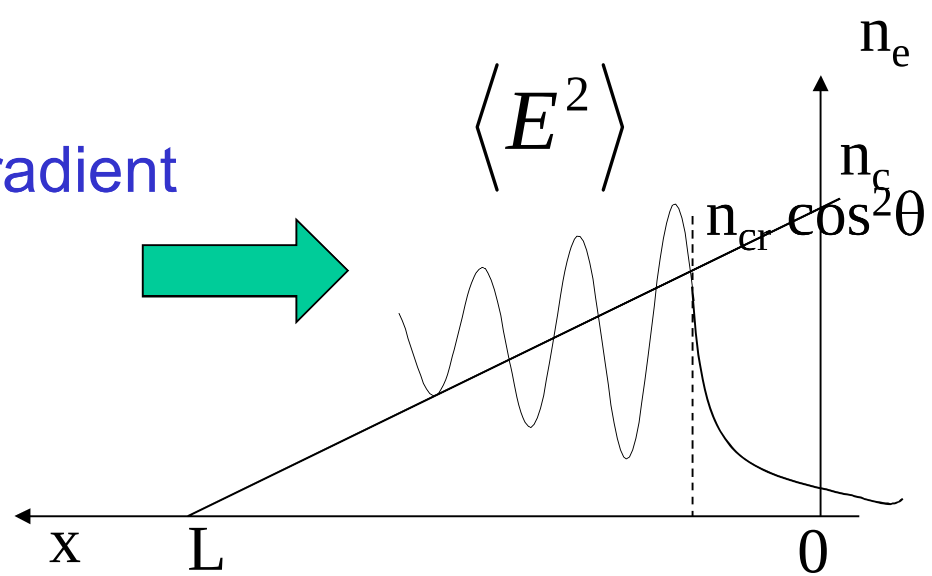
$$\delta n_e \propto \frac{\vec{E}.\vec{\nabla} n_e}{n_e - n_c}$$

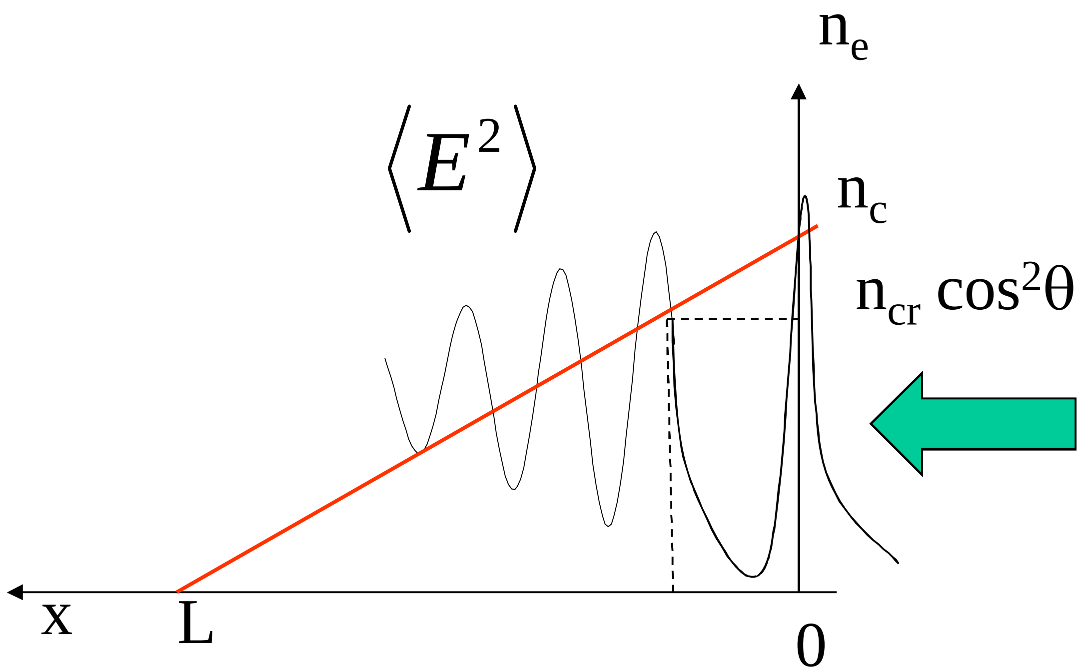
Obliquely incident *p*-polarized light on a linear density ramp s-polarized light

• no component along the gradient

• so no resonance at n_c

→ no wave set-up





p-polarized light $\vec{E}_L.\vec{\nabla}n_e \neq 0$

• a finite component along the gradient

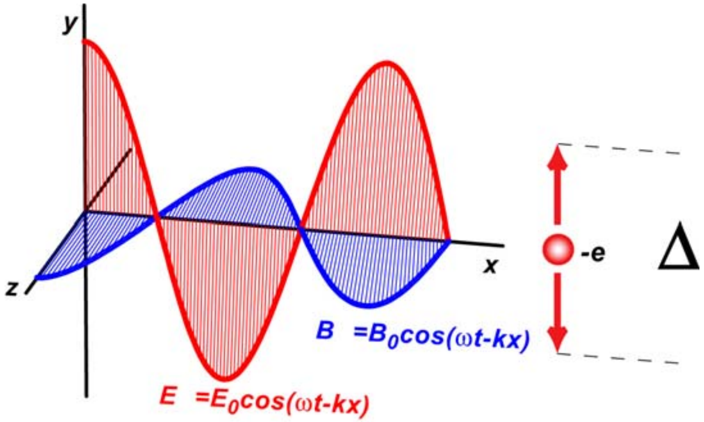
• undergoes a resonance at n_c

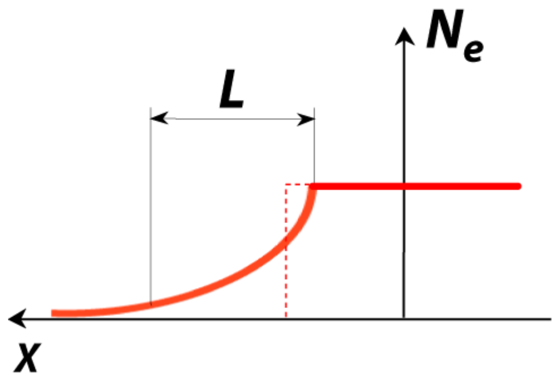
• builds up a wave along the gradient

•***HOT electron generation***

Noncollisional Absorption
Very Steep Gradient

electron oscillation





$L << \lambda$

plasma

- $\Delta < L$
- $\Delta > L$

How is the laser energy shared in the plasma?

1. Bulk of the Electrons, primarily IB heated (quasi-equilibrium, Maxwellian, T_e upto a few 100 eV)

2. `Hot' Electrons, created by collective mechanism (RA) (non-equilibrium, some times `beam-like', but can be approximated by another Maxwellian at a much higher `temperature') T_{hot} : 10–100 keV.

These `hot' electrons

(1) Cause giant magnetic fields
(2) penetrate into the bulk,create inner shell vacancies and K, L x-rays. Also emit hard-very hard bremsstrahlung, cause ion acceleration…….

(Some of these electrons also escape into vacuum)

Energy budget for the given laser input:

At 10^{16} W /cm^2

IB absorption ~ 10%

Resonance Absorption ~ 30-40%

Other Collective mechanisms ~ 10%

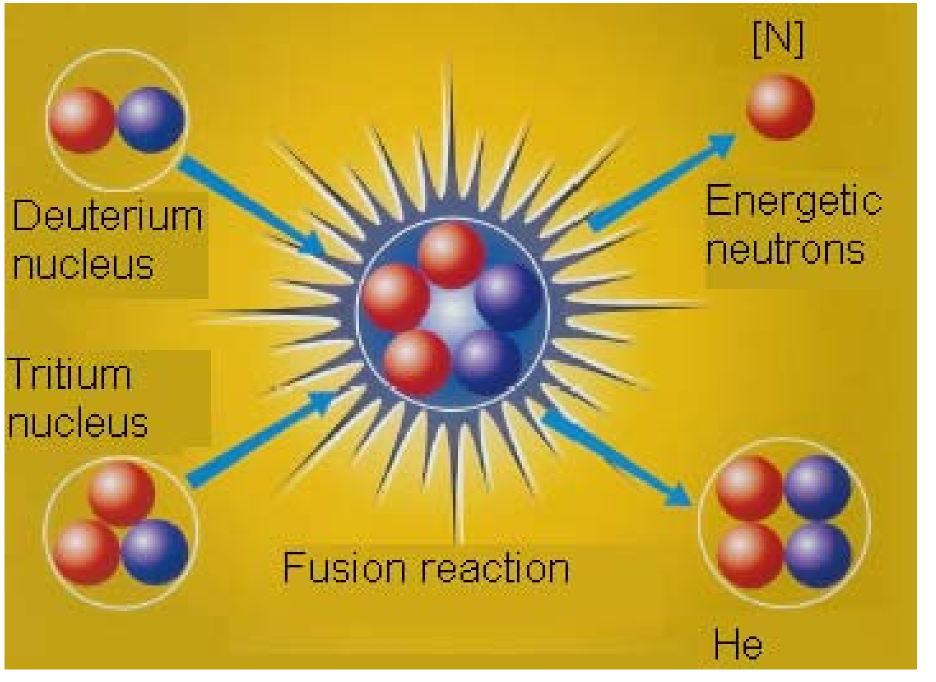
The rest is not coupled !

Why are Hot electrons Important?
An example- laser fusion

NUCLEAR FUSION

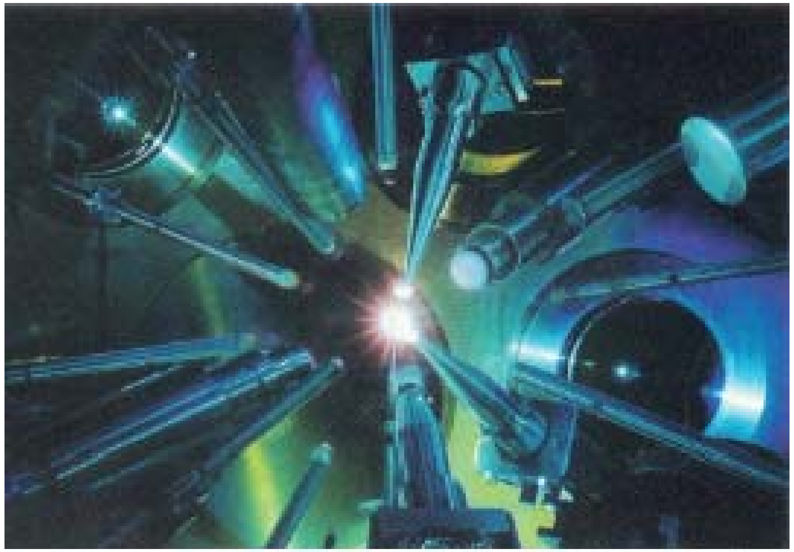
$$D + T \rightarrow {}^{4}He(3.52\ MeV) + n(14.06\ MeV)$$

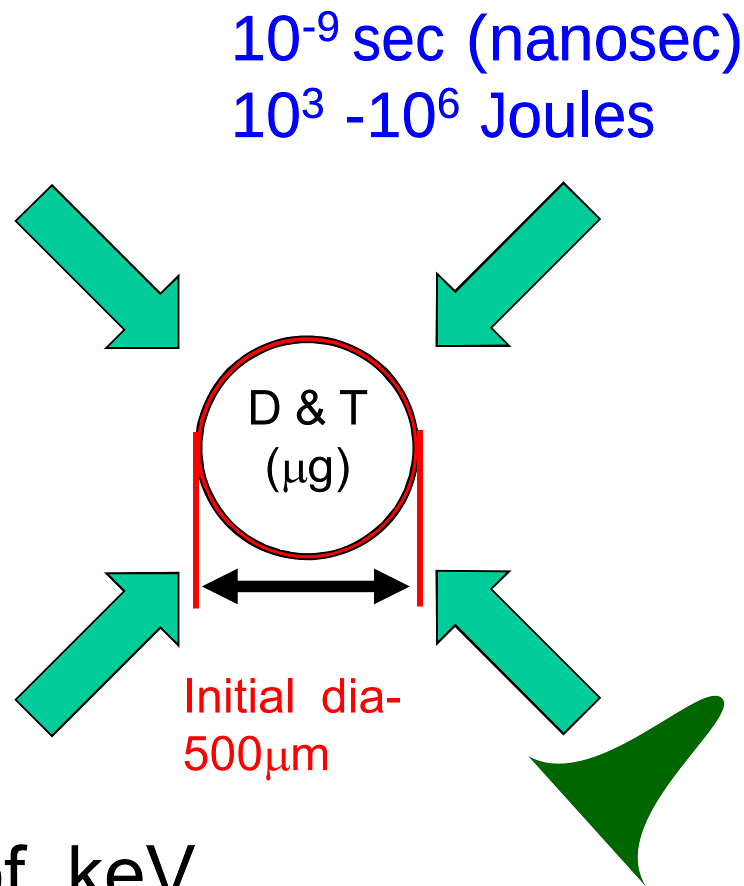
For
further heating



Neutron energy can be harnessed.

LASER FUSION



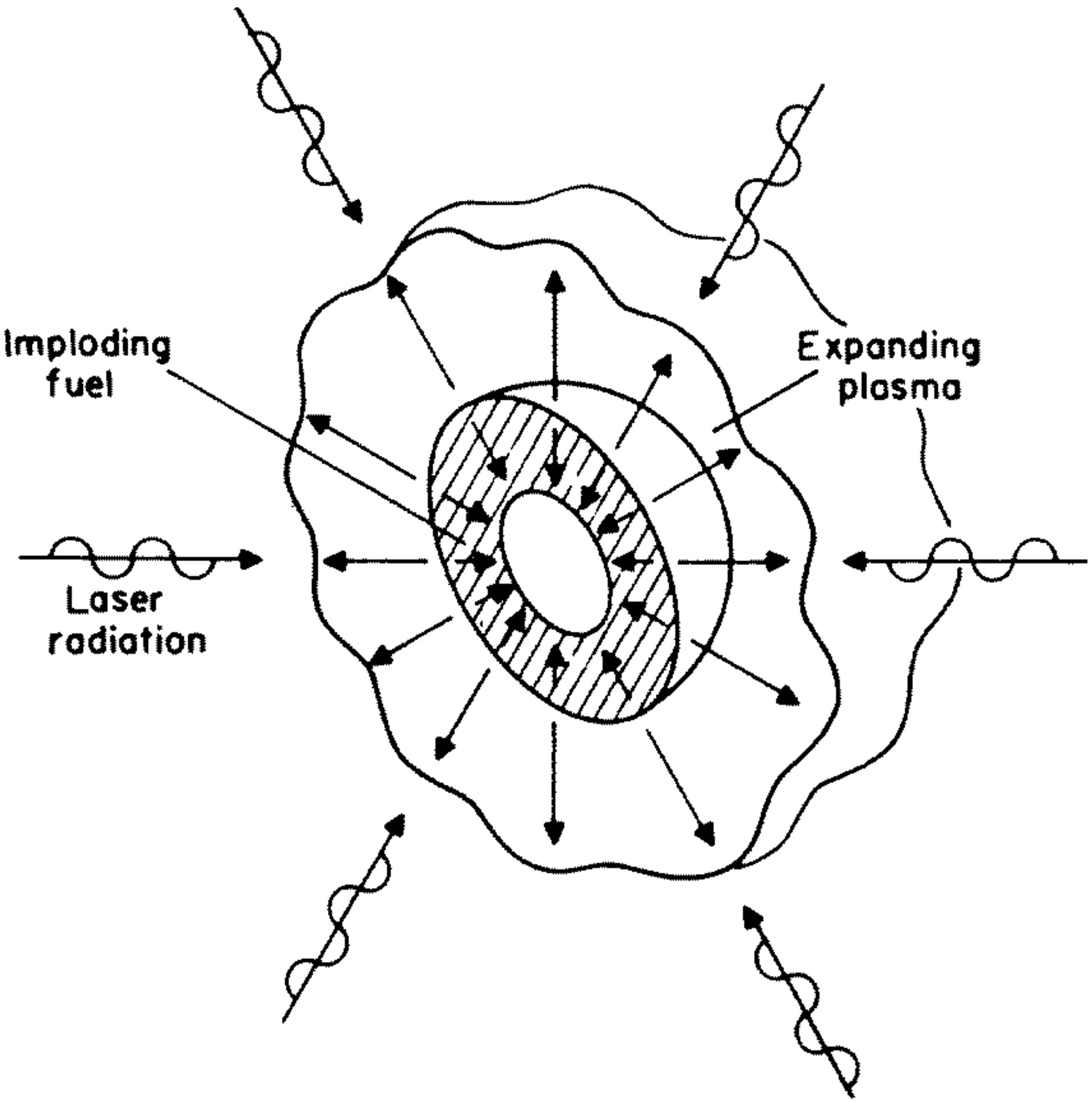


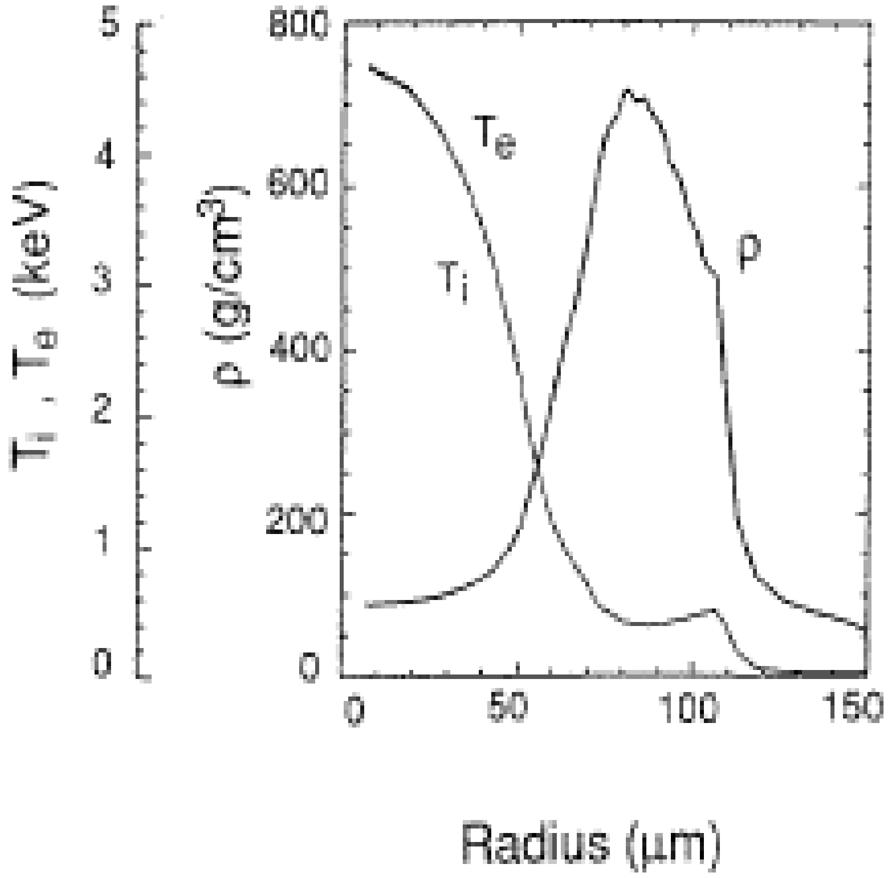
Reqd. D,T Ion Temp. ≈ 10-100s of keV

Compression upto 1000 times liquid density

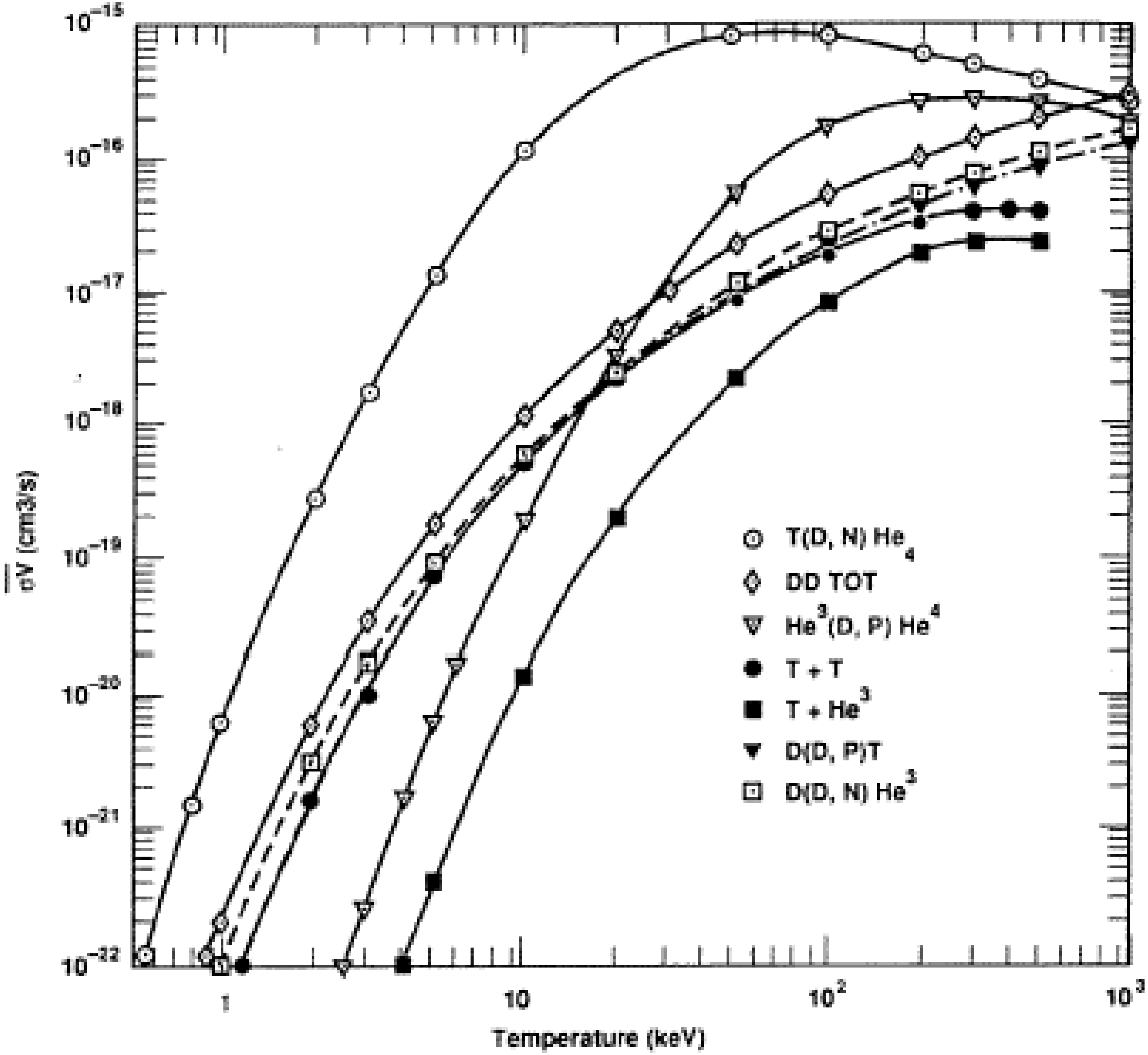
Fusion of large numbers of D and T → Net energy gain (more than the power sent in).

Gain of at least 100 required for power plant


Imploding
fuel
Expanding
plasma
Laser
radiation



5
4
3
2
1
0
T_i , T_e (keV)
800
600
400
200
0
ρ (g/cm³)
T_e
T_i
ρ
0
50
100
150
Radius (μm)



10^−15
10^−16
10^−17
10^−18
10^−19
10^−20
10^−21
10^−22
σV (cm3/s)
1
10
10^2
10^3
Temperature (keV)
T(D, N) He4
DD TOT
He3(D, P) He4
T + T
T + He3
D(D, P)T
D(D, N) He3

The FAST IGNITION Scheme of Laser Fusion
(Basov et al., 1992, Tabak et al, 1994)

A new proposal to realize net gain by Laser Fusion-

the basic idea-

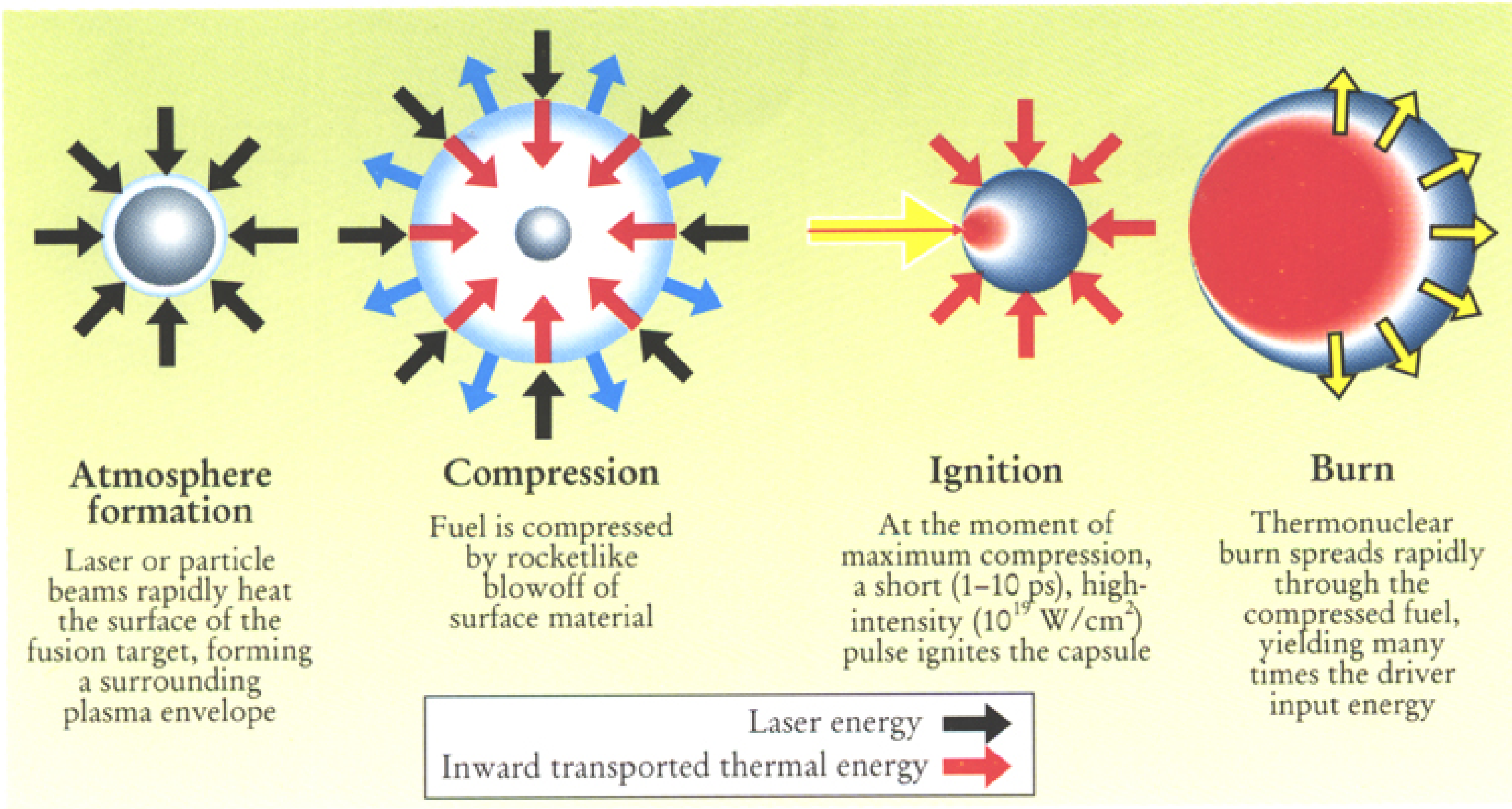
two steps

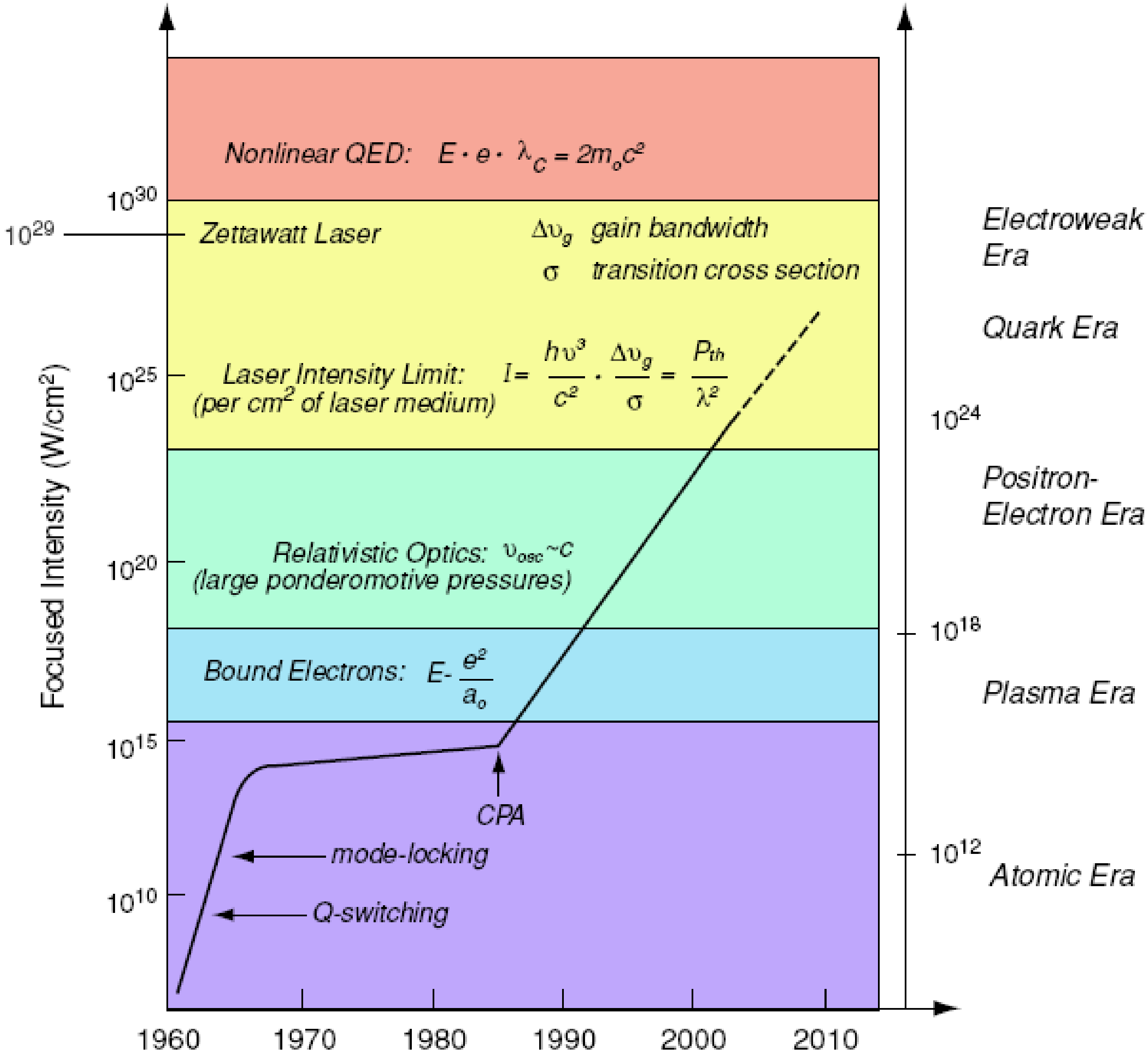
1. **Compress the fusion target by many nanosecond, high energy beams**

2. At peak compression, send a femtosecond/picosecond pulse to create 'Hot' electrons.

These will ignite the target.

Fast Ignition of Fusion

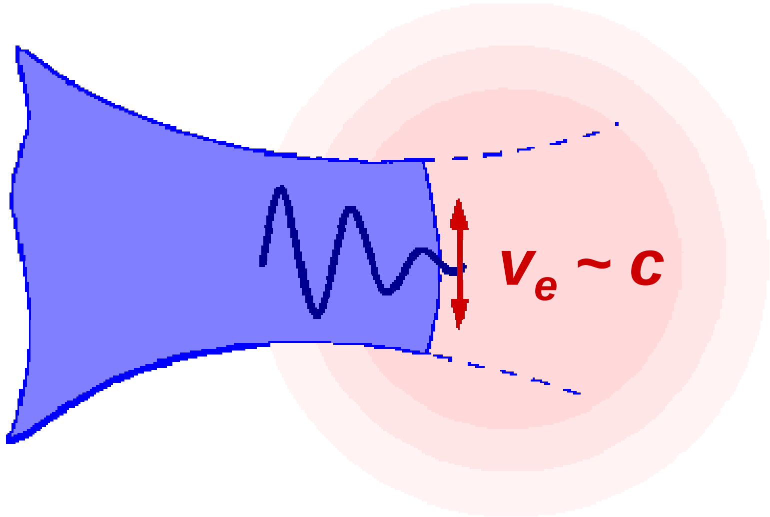




Nonlinear QED: $E \cdot e \cdot \lambda_C = 2m_oc^2$
10^{30}
10^{29}
Zettawatt Laser
$\Delta\upsilon_g$ gain bandwidth
σ transition cross section
Laser Intensity Limit: (per cm^2 of laser medium)
$I = \frac{h\upsilon^3}{c^2} \cdot \frac{\Delta\upsilon_g}{\sigma} = \frac{P_{th}}{\lambda^2}$
10^{25}
Relativistic Optics: $\upsilon_{osc} \sim c$ (large ponderomotive pressures)
10^{20}
Bound Electrons: $E \sim \frac{e^2}{a_o}$
10^{15}
10^{10}
CPA
mode-locking
Q-switching
Focused Intensity (W/cm^2)
1960
1970
1980
1990
2000
2010
Electroweak Era
Quark Era
10^{24}
Positron-Electron Era
10^{18}
Plasma Era
10^{12}
Atomic Era

For laser intensities exceeding *$I \sim 10^{18}$ W/cm^2*, the electron quiver motion becomes relativistic within half a period

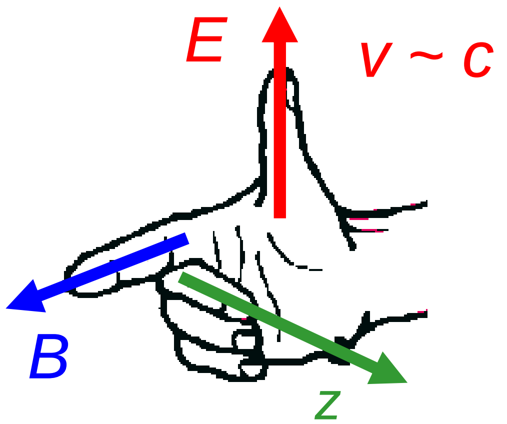
target: one electron



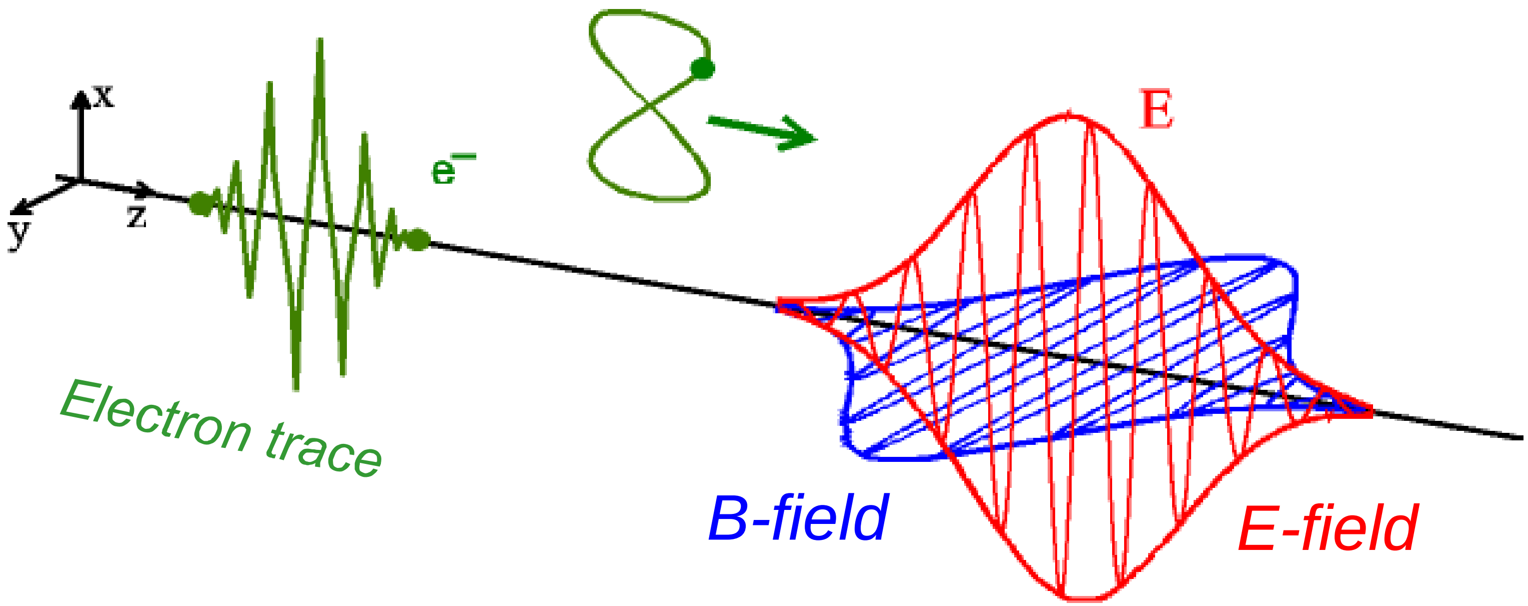
- ***mass increase***
- ***forward acceleration due to Lorentz force***
- ***anharmonic osc.***

$$a_0 = \frac{eE_0}{\omega m_e c} \qquad I = \frac{E_0 B_0}{\mu_0} = \frac{E_0^2}{\mu_0 c} = \frac{a_0^2}{\lambda^2[\mu m]} \cdot 1.4 \cdot 10^{18} \frac{W}{cm^2}$$

single electron dynamics



$$\vec{F} = e\vec{E} + e\,\vec{v} \times \vec{B} \qquad \left(B_0 = E_0 / c\right)$$



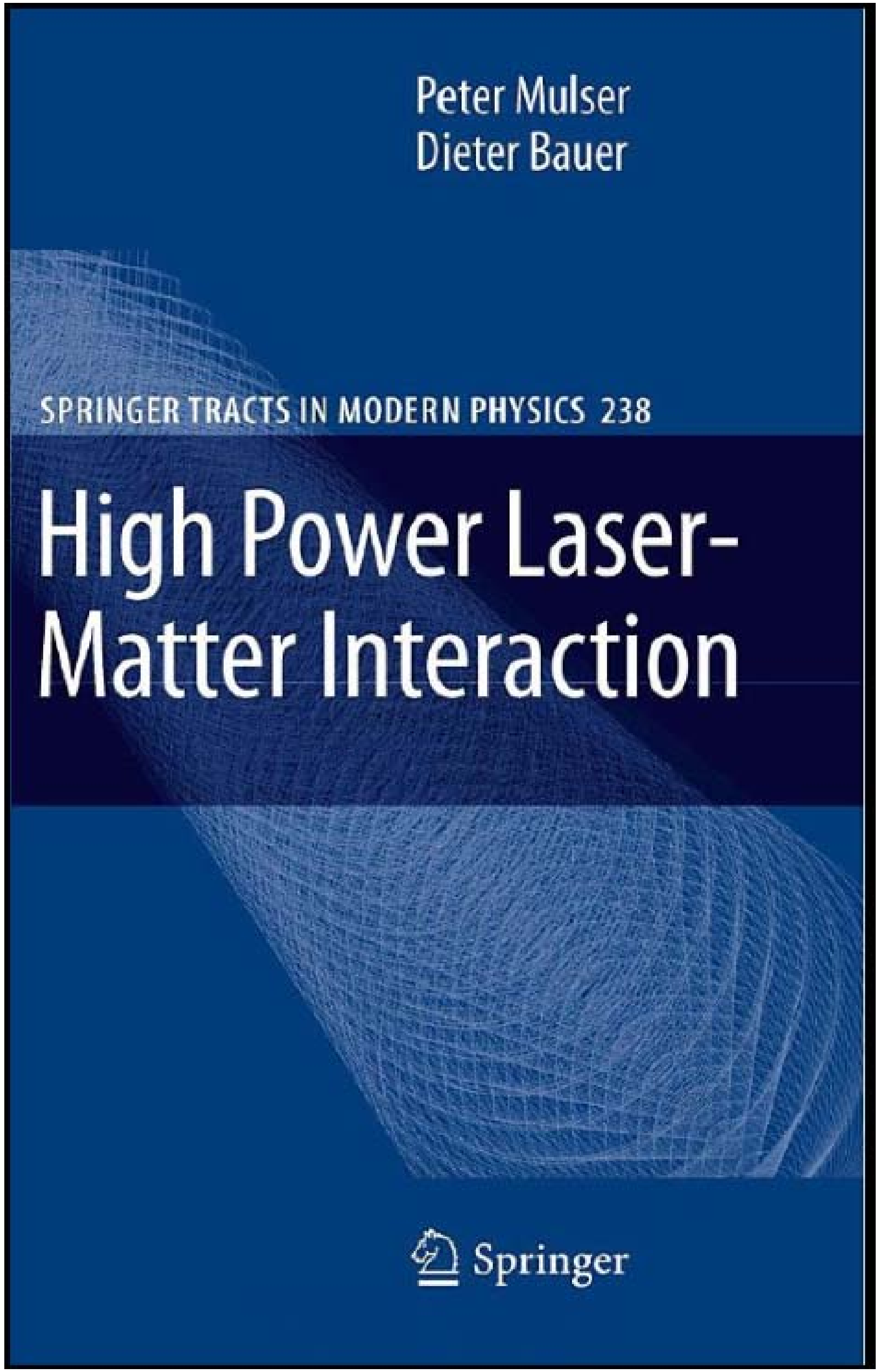
In the next two lectures, we will see the
Physics of Hot Electrons

Specifically,

(a) controlling their creation

and

(b) Consequences of their transport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Optics in the relativistic regime

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Relativistic high-power laser–matter interactions

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Intense, ultrashort light and dense, hot matter

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Abstract. This article presents an overview of the physics and applications of the interaction of high intensity laser light with matter. It traces the crucial advances that have occurred over the past few decades in laser technology and nonlinear optics and then discusses physical phenomena that occur in intense laser fields and their modeling. After a description of the basic phenomena like multiphoton and tunneling ionization, the physics of plasma formed in dense matter is presented. Specific phenomena are chosen for illustration of the scientific and technological possibilities – simulation of astrophysical phenomena, relativistic nonlinear optics, laser wakefield acceleration, laser fusion, ultrafast real time X-ray diffraction, application of the particle beams produced from the plasma for medical therapies etc. A survey of the Indian activities in this research area appears at the end.

Keywords. Laser-driven acceleration; frequency conversion; harmonic generation; ultrafast processes; relativistic plasmas.

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