I. Basic concept of laser-plasma interaction

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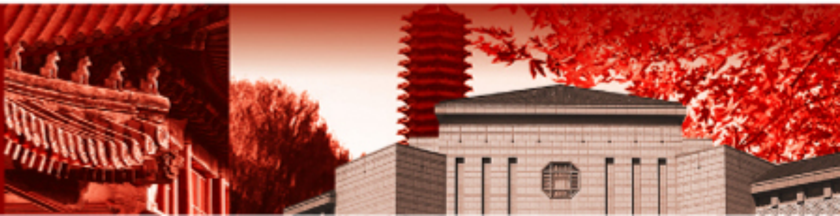
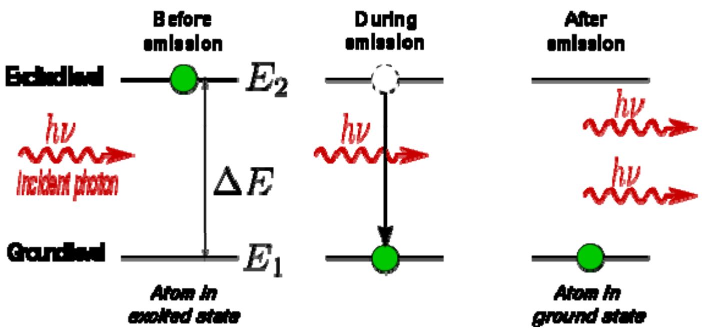


What is Laser?

Laser—Laser Amplification by Stimulated Emission of Radiation

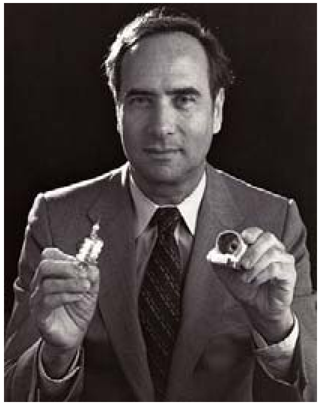
Stimulated Emission



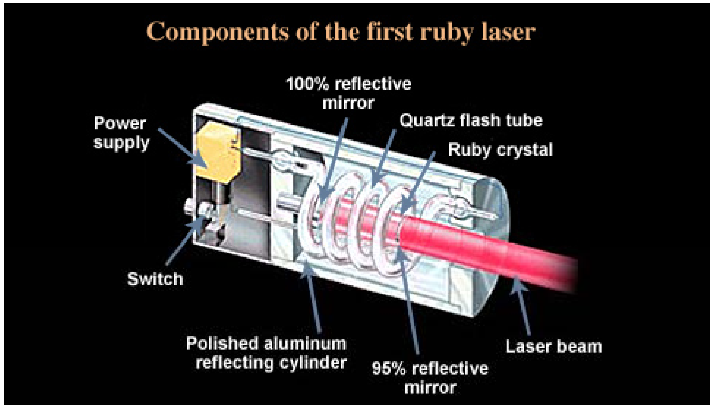
$$E_2 - E_1 = \Delta E = h\nu$$

EINSTEIN, ALBERT. Strahlungs-Emission und -Absorption nach der Quantentheorie [Emission and Absorption of Radiation in Quantum Theory]. Verhandl. D. Deutch. Phys. Ges., 1916, Vol 18, pp. 318-323.

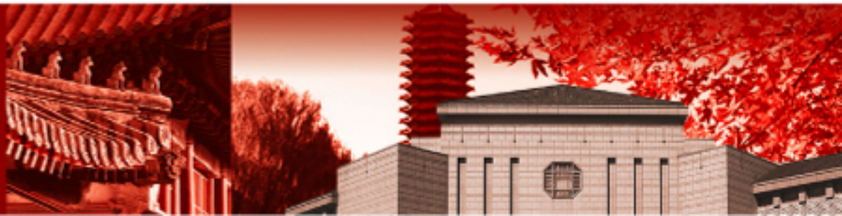
EINSTEIN, ALBERT. Zur Quantentheorie der Strahlung [On the Quantum Theory of Radiation]. Phys. ZS., 1917, Vol. 18, pp. 121-128.



Theodore Harold Maiman



T. H. Maiman, Nature, 187, 493 (August 6, 1960)



Key laser parameters

1. Power

$$P_L = \frac{\xi_L}{\tau},$$ ξ_L: laser energy, τ: pulse duration (FWHM)→ fs to ns

Units : J/s (W) ; range from 10^{-6}W to 100s of TW (Terawatt, 10^{12}W) up to Petawatt

2. Intensity

$$I_L = \frac{P_L}{S} = \frac{\xi_L}{S\tau}, S = \pi r^2$$: the area of laser focal spot

Units : W/cm^2; range from 10^{14}~10^{15} W/cm^2 (conventional ICF), 10^{18}~10^{24} W/cm^2

3. Electric field

$$E_L = \left(\frac{8\pi I_L}{c}\right)^{1/2} = 2.75\times10^{3} I_L^{1/2} (V/m),$$

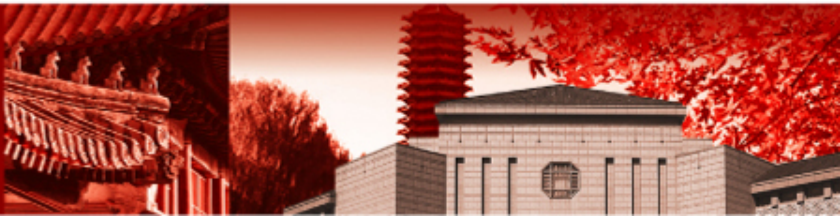
4. Wavelength and frequency

$$\lambda_L = \frac{2\pi}{k_L} = \frac{2\pi c}{\omega_L},$$

$\lambda_L = 1.053\mu m$: Nd glass laser

$\lambda_L = 10.6\mu m$: CO_2 laser

$\lambda_L = 0.35\mu m$, 3ω laser (ICF)



Key laser parameters

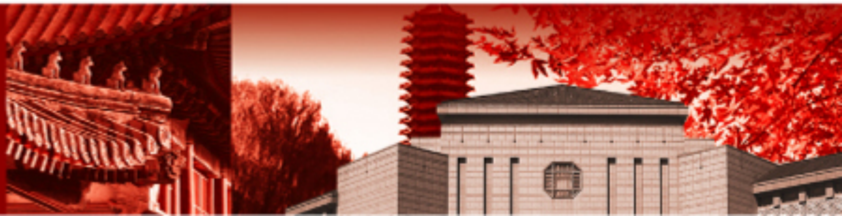
Normalized laser amplitude $a_0 = eE_0 / m_e c\omega_0$

$$a_0 = 8.5\times10^{-10}[I(W/cm^2)\lambda_L(\mu m)^2]^{1/2}$$

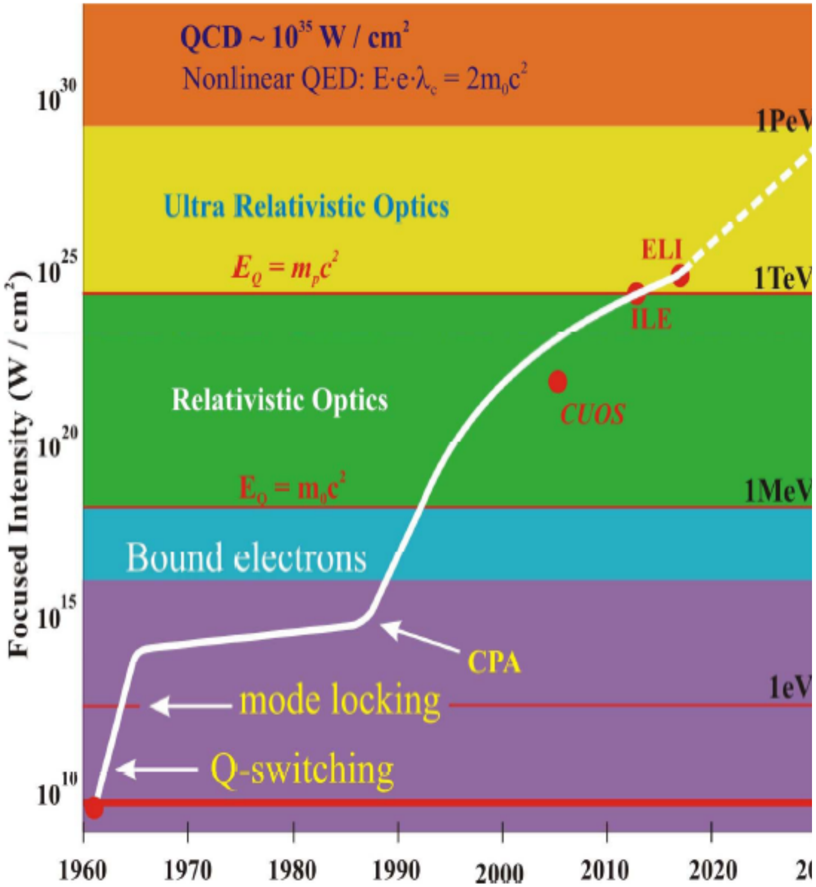
I_0 (W/cm^2)	10^{16}	5×10^{16}	10^{17}	5×10^{17}	10^{18}	5×10^{18}	10^{19}	5×10^{19}	10^{20}	10^{21}
a0 (λ_0=1μm)	0.084	0.187	0.265	0.592	0.837	1.8714	2.65	5.92	8.37	26.5

$$I\lambda_L^{\ 2} = 1.37\times10^{18} W\cdot cm^{-2}\cdot\mu m^{-2},\quad v\sim c$$

电子的quiver速度等于光速，或者，电子的颤动能量等于其静止能量。



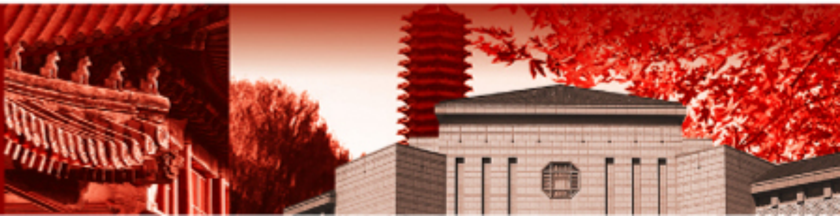
Laser progress



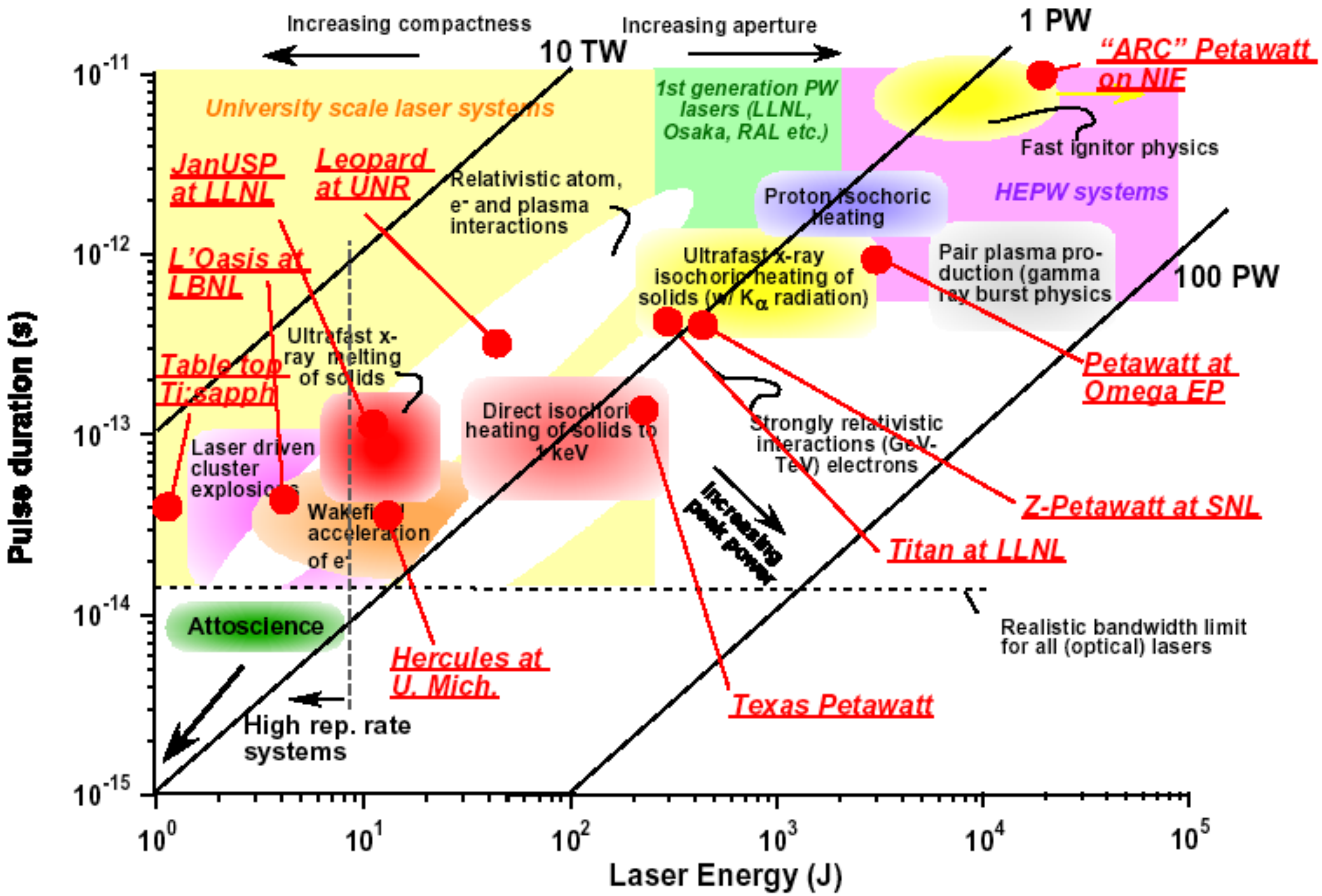
Amplitude $\left[a_0 = \frac{eE_0}{m_e c\omega}\right]$	Intensity $\left[\frac{\text{W}}{\text{cm}^2}\right]$	Regime
$a_{QED} = \frac{m_e c^2}{\hbar\omega}$	2.4×10^{29}	e^+, e^- in vacuum
$a_{QM} = \frac{2e^2 m_e c}{3\hbar^2\omega}$	5.6×10^{24}	quantum effects
$a_p = \frac{m_p}{m_e}$	1.3×10^{24}	ultra - relativistic p
$a_{rad} = \left(\frac{3\lambda}{4\pi r_e}\right)^{1/3}$	1×10^{23}	radiation damping
$a_{rel} = 1$	1.3×10^{18}	relativistic e^-

$$a_0 = \frac{p_{osc}}{m_e c} = \frac{eE_0}{m_e \omega c} = \sqrt{\frac{I\lambda_{\mu m}^2}{1.37 \times 10^{18}}}$$

Normalized laser amplitude



Laser progress



Courtesy of Prof. Todd Ditmire, UT Austin

What is plasma?

Plasma: A plasma is a quasineutral “gas” of charged and neutral particles which exhibits collective behavior. (F. F. Chen) 通过长程**Coulomb**力而集体相互作用着的运动带电粒子（电子、离子或部分中性粒子）的电中性集合。

Because the plasma is composed of charged particles, the electromagnetic fields govern their motion, and the motion changes the electromagnetic fields in turn. 含有大量的自由带电粒子，以致其动力学行为受电磁力支配的物质状态

Therefore, the particle motion and the EM fields are strongly coupled.
The plasma properties appears only when a gas is ionized sufficiently that the electric characters are more significant than the neutral characters.

By “collective behavior”, which means that depend not only on local conditions but on the state of the plasma in remote regions as well.

Collisionless plasma: The long range EM force is much larger than the local force associated with collisions.

What is plasma?

Quasineutral:

1. 正负电荷任何明显的不平衡，需要极强的电场才能维持---电荷分离场

在1.053μm的激光等离子体的临界面（$n_{cr}=10^{21}cm^{-3}$）处，偏离电中性仅1%，

电场强度：

$$E = \frac{4}{3}\pi r^3 \frac{n_{cr}}{10^6}\frac{e}{r^2} = 6\times 10^9 r(V/m)$$

2. 任何等离子体都有一个自然振荡频率ω $_p$

$$n(r,t) = n_0 + n'(r,t),$$

$$n_i = n_0, |n'| << n_0$$

$$\nabla \cdot E = -4\pi n' e$$

$$m_e \frac{\partial u}{\partial t} = -e\vec{E}$$

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{u}) = 0$$

$$\frac{\partial^2 n'}{\partial t^2} + \frac{4\pi n_0 e^2}{m_e} n' = 0$$

$$\omega_p = \left(\frac{4\pi n_0 e^2}{m_e}\right)^{1/2} = 5.65\times 10^4 \sqrt{n_0}\,(s^{-1})$$

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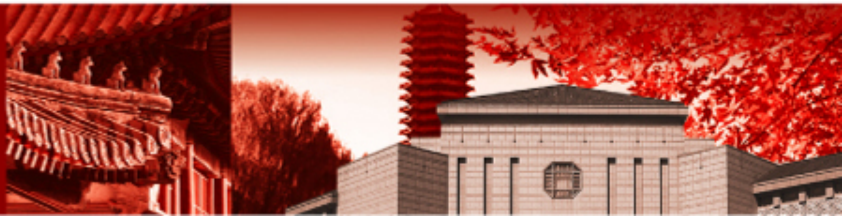


What is plasma?

Quasineutral:

3. **“准中性”(quasineutral)：** 等离子体行为的一个基本特征是它具有屏蔽掉作用于它上面的电势的能力。等离子体中性到可以取$n_i \approx n_e \approx n$(其中n是公共密度，称为等离子体密度)，但是还没有中性到所感兴趣的电磁力都消失。

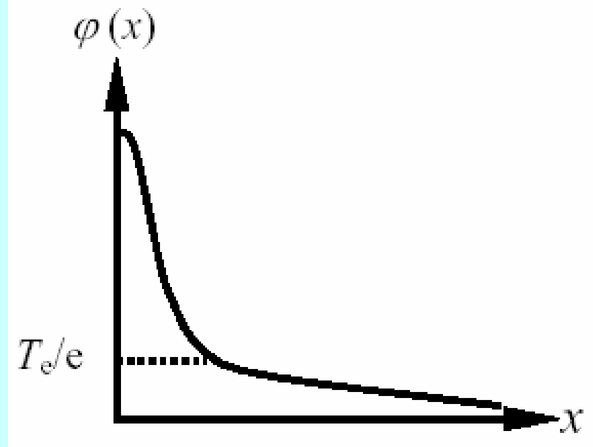


图 1.2 等离子体鞘电势分布

λ_D的物理意义有两个方面：

• 静电作用的屏蔽半径；

• 局域性电荷分离的空间尺度。 $\lambda_D = v_{th} / \omega_p$

(热运动的空间尺度)

$$\lambda_D == \sqrt{\frac{kT_e}{4\pi ne^2}}, \phi = \phi_0 e^{-|x|/\lambda_D}$$

Derivation of Debye Length

平衡等离子中：$n = n_0 \exp(e\varphi / k_B T)$

φ 是由于电荷扰动引起的位势，假定离子不动，并取 $n' = n'\delta(r)$

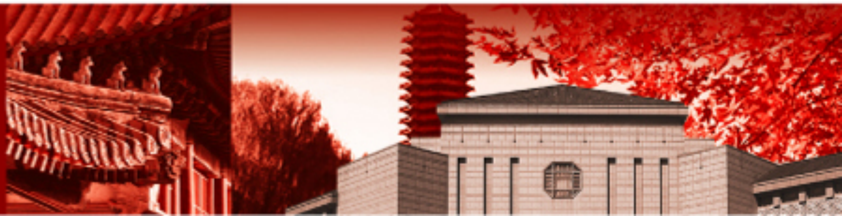
则当距离远在 $e\varphi(r) / k_B T << 1$ 处，

$$\nabla^2 \varphi = -4\pi[en_0 - en_0 \exp(e\varphi / k_B T) - en'\delta(r)]$$

$$\approx \frac{4\pi n_0 e^2}{k_B T}\varphi + 4\pi en'\delta(r)$$

方程的解为：$$\varphi(r) = -\frac{en'}{r}\exp(-r/\lambda_D)$$

$$\lambda_D = \left(\frac{k_B T}{4\pi n_0 e^2}\right)^{1/2}$$



Three criterions of a plasma system

1) λ_D<<L,系统的空间尺度远远大于λ_D;　　宏观电中性

如果系统的尺度L大于λ_D，那么，每当出现电荷的局部集中或者在系统中引入外电势时，它们就在比L短的距离被屏蔽，使等离子体的大部分免受大电势或电场的影响。

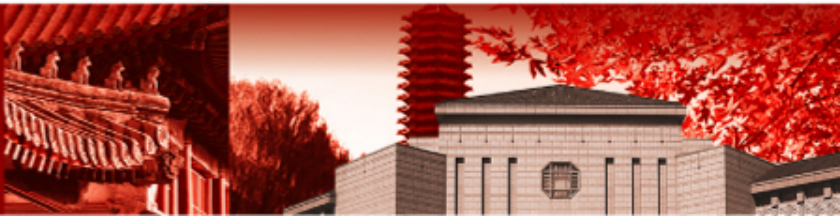
一个电离气体成为等离子体的一个判据是：气体足够稠密，以使 λ_D<<L。

2) N_D>>>1,德拜球内的粒子数远远大于1，是集体相互作用度量

;倘若在鞘层区域只存在一个或二个粒子，那么德拜屏蔽就不是一个统计上正确的概念。

等离子体参量

$$N_D = n\frac{4}{3}\pi\lambda_D^{\ 3} = \frac{4}{3}\pi\frac{kT_e}{4\pi e^2}\sqrt{\frac{kT_e}{4\pi n e^2}}$$



Three criterions of a plasma system

3) ωτ>1,系统平均碰撞时间远远大于等离子体特征振荡周期，不影响等离子体本征电磁耦合运动。　该条件和碰撞相关

L:系统尺度；τ:带电粒子与中性原子碰撞的平均时间；ω：典型的等离子体振荡频率

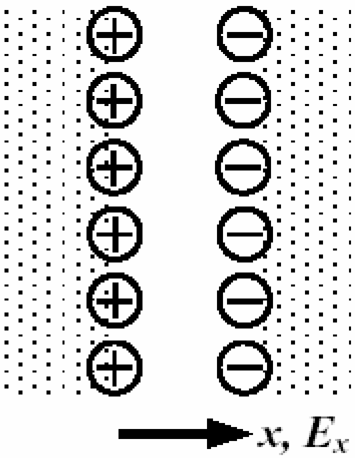


图 1.3　等离子体振荡示意图

Key plasma parameters

1. Debye length

$$\lambda_D = (\frac{T_e}{4\pi n_0 e^2})^{1/2},$$

- Screen radius of the electrostatic potentials
- Local spatial dimension of charge separation

2. Critical density of laser propagation:

$$\omega^2 = \omega_{pe}^2 + c^2 k^2 \Rightarrow n_c = \omega_0^2 m_e / 4\pi e^2 = 1.1 \times 10^{21} / \lambda_L^2$$

3. Group, phase velocity and refractive index laser propagation:

$$v_g = \frac{d\varpi}{dk} = c\sqrt{1 - \frac{\varpi_{pe}^2}{\varpi^2}} = c\sqrt{1 - \frac{n_e}{n_{cr}}}$$

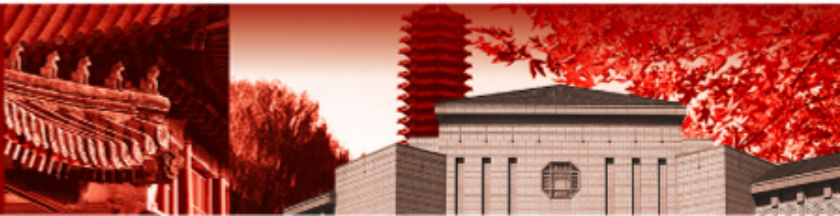
$$v_p = \frac{\varpi}{k} = \frac{c}{\sqrt{1 - \frac{\varpi_{pe}^2}{\varpi^2}}} = \frac{c}{\sqrt{1 - \frac{n_e}{n_{cr}}}}$$

$$\eta = \frac{c}{v_p} = \frac{v_g}{c} = \sqrt{1 - \frac{\varpi_{pe}^2}{\varpi^2}} = \sqrt{1 - \frac{n_e}{n_{cr}}}$$

Laser propagation always from low to high refractive index → from high to low plasma density region

4. Plasma density scale length:

$$L = (\frac{1}{n} \cdot \frac{dn}{dx})^{-1} \quad n = n_0 \exp(-x / L)$$



谢 谢!