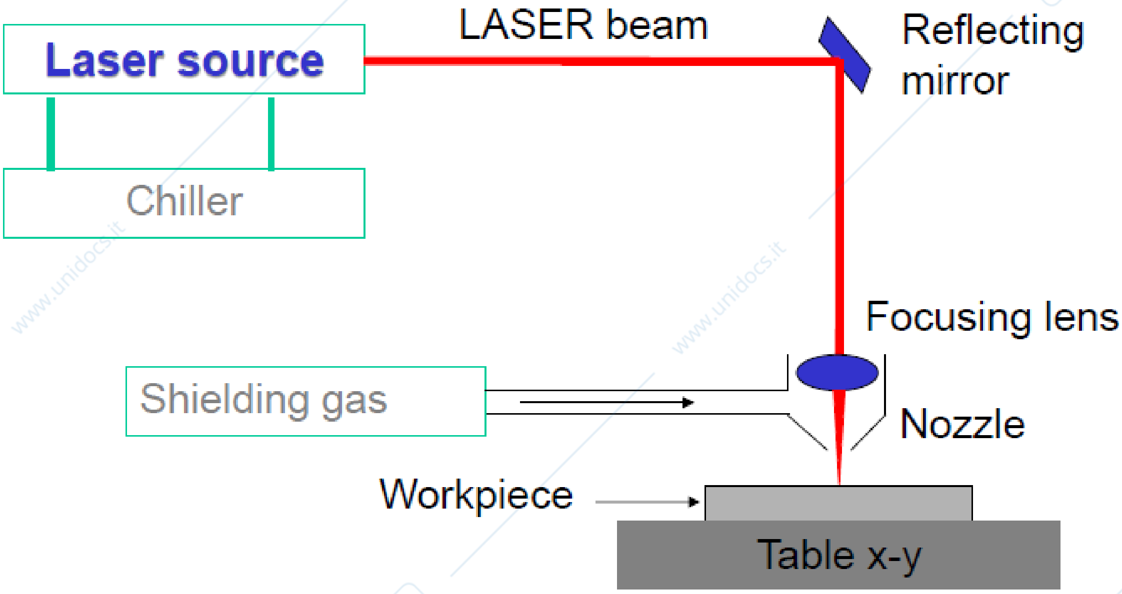
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

LASER FUNDAMENTALS

LASER SYSTEM

Laser is a very versatile tool which is used in many applications, not only in manufacturing but also in other fields as medical, measurements etc.



From a manufacturing point of view we need to have:

- A source of our laser, this can be based on a gas active medium, a solid state active medium (a crystal generally), a diode or a fiberglass.
- Reflecting mirrors that have the purpose of direct to the target our laser. We always need mirror because the laser source should be still and horizontal to maintain its stability; the unique case in which we don't need mirrors is if we use fiberglass: laser beam is conveyed inside the fiber and the fiber can be bent, so we can direct the laserbeam where we want.
- Laser head or laser torch where we focus the laser beam on to a tiny spot, so we need to have focusing lens inside the laser head in order to have a spot as small as possible. The smaller the spot size the better the process (higher power density).
- Sometimes you need a shielding gas (gas protettivo) that shields the lens in order to protect lens but also to protect from oxidation the target material.
- Workpiece which needs to be moved at least on horizontal plane (x-y axes), but in some other layouts we might move the head rather than the workpiece, this depends on how we are able to deliver the beam on to the target.

LASER-MATERIAL INTERACTION

Why the laser heats up the material? Because the energy of the beam can be absorbed by the material. The energy of the beam is an electromagnetic energy because the laser light

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

is an electromagnetic wave. In general this EM wave has a low frequency because usually it is close to the visible region of frequencies, this small frequency has not the ability to interact with the nuclei of the atoms, it generally interacts with the electrons of our target materials; the clouds of electrons are excited by the beam, and this excitation transforms in heat on a macroscopic scale and as a consequence there is a temperature increase. So, in many cases we can model the laser beam (the laser spot) as an heat source. The way the material interacts with the laser beam depends on:

- Frequency of electromagnetic wave.
- Structure of the material: it can be amorfous (glass), it can be a metal (ordered structure) etc.

While the energy of the beam is absorbed it is transformed into heat inside the material, so how deep can a laser beam be transmitted inside the material? If we have an incident laser beam of power intensity I_i, part of this laser power will be reflected (we can call the reflected fraction I_r), and part of this power (hopefully most of it) will be transmitted (I_t) inside the material. For example, if the material is transparent or very thin, the laser beam is transmitted but it can also go outside the material without being absorbed, this is not what we want. So, we would like the material to dissipate the energy of the incident beam in a short thickness. We can write the transmitted power as a fraction of the incident power:

$$I_t = AI_i$$

Where A depends on the surface of the material (roughness, nature of the material and color of the material) and it is called "absorption coefficient".

This transmitted power will be dissipated according to an exponential law with a negative exponent: Beer-Lambert law.

$$I_t(z) = I_t(0)e^{-2\alpha z} = AI_ie^{-2\alpha z}$$

Beer-Lambert law

If we calculate ***It*** at a depth ***s=1/α***

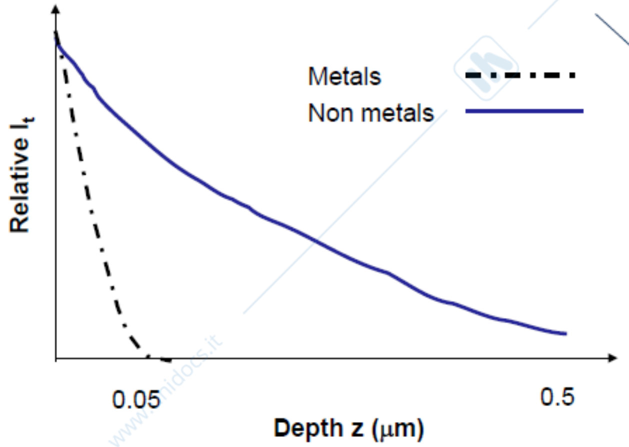
$$I_t(z=s) = I_t(0)e^{-2\alpha z} = I_t(0)e^{-2} = 0.135I_t(0)$$

$$I_t(2s) = 0.018AI_t(0)$$

α = absorption factor

s = skin thickness

(or ATTENUATION LENGHT)



- *At a depth (skin thickness) equal to s, the transmitted power is cut down by about 86%*
- *At a depth (skin thickness) equal to 2s, the power is reduced by 98 %*

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

$$I_t(z) = I_t(0)e^{-2\alpha z} = AI_i e^{-2\alpha z}$$

As we goo deeper into the material the transmitted power is progressively reduced (exponentially reduced) → it is absorbed by the material. The trend of the exponential depends on α which is called "absorption factor". Then, we can define the reciprocal of α which we can call "skin thickness" or"attenuation length" (s): if we go at a depth inside the material which is equal to s, we can see that the amount of intensity will be:

$$I_t\left(\frac{1}{\alpha}\right) = I_t(0)e^{-2\alpha\frac{1}{\alpha}} = I_t(0)e^{-2} = I_t(0)0{,}135$$

86% of the energy is absorbed by the material at a depth equal to the skin thickness. If we go at twice the skin thickness:

$$I_t(2s) = 0{,}018 I_t(0)$$

The intensity of our power is 1,8% of the initial one, it means that 98,2% of the initial energy has already been absorbed by the material.

Therefore, the skin thickness, which is a property of the material, is very relevant for a manufacturing point of view because if the skin thickness is very large it means that the material is transparent→ it could happen that the laser beam crosses the material without heating it significantly. On the contrary, for metals the s is small and it means that the electrons of a metal are able to be excited in a very short length and so this kind of material can be heated up efficiently.

Finally, the way the material absorbs the radiation depends on :

- Absorption coefficient A, we would like A to be possibly equal to 1.
- Skin thickness, we would like s to be smaller than the thickness of our material, generally we prefer it to be as small as possible; but this depends on the application.

Remember that A and s depends on the nature of the material but also on the frequency of the wave or on the wavelength of the wave.

APPLICATIONS

Cutting
Welding
Heat treatment
Drilling
Marking
Scribing, milling
Cleaning
Measurement

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

ELECTROMAGNETIC FIELD

An electromagnetic field is composed of an electric field which is ortogonal to a magnetic field, the electromagnetic wave will travel in a given direction. We can define mathematically define the EM wave as a function of space and time:

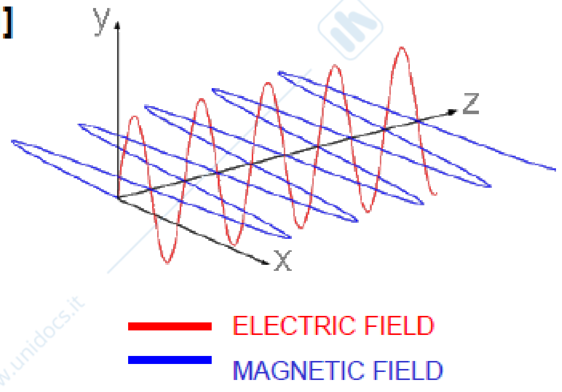
ω: angular velocity [rad/s]

φ: phase [rad]

$$E_y(z,t) = E_{y0} \cdot sen(\omega t - \gamma z + \varphi)$$

ω=2πf: angular velocity [rad/s]
λ: wave lenght [m]

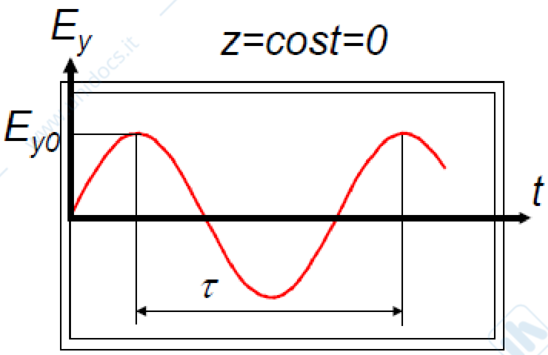
$$\lambda \cdot f = v$$



$$E_y(z,t) = E_{y0} \cdot sen\left(\frac{2\pi}{\lambda}(vt - z) + \varphi\right)$$

v: travel velocity [m/s]
(vacuum: *v*=*c*=3*10^8 m/s)

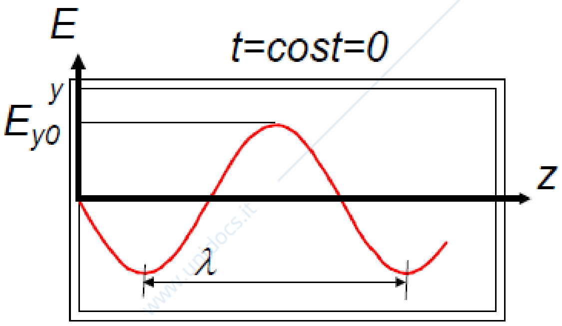
V is the propagation velocity of the laser beam inside a given medium, wavelength and frequency are 2 characteristics of the EM wave and they are correlated through v. In vacuum v=c (speed of light in vacuum). After having defined λ and f, we can rewrite the first equation in the figure above and we can obtain the second equation. Notice that the equation is periodic both in term of time and space.



$$E_y(z,t) = E_{y0} \cdot sen(\omega t - \gamma z + \varphi)$$

$$E_y(z,t) = E_{y0} \cdot sen\left(\frac{2\pi}{\lambda}(vt - z) + \varphi\right)$$

ω=2πf: angular velocity [rad/s]
λ: wave lenght [m]



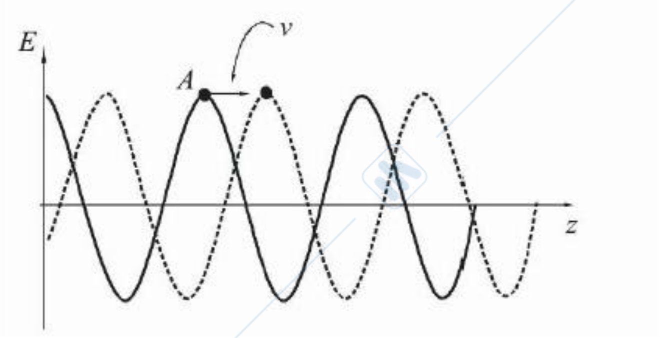
$$\boxed{\lambda \cdot f = v}$$

τ: period [s]
f=1/ *τ* : frequency [Hz=1/s]
v: velocity [m/s]
(vacuum: *v*=*c*=3*10^8 m/s)

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

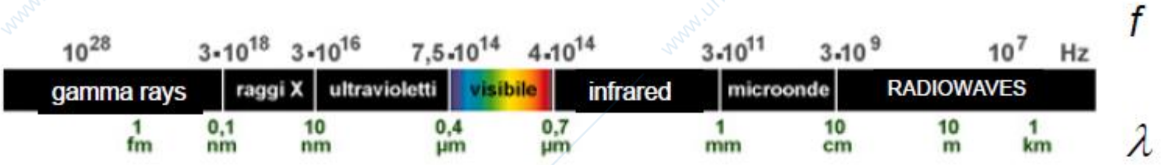
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

ELECTROMAGNETIC SPECTRUM



$$\lambda \cdot f = v$$

λ:	wave lenght	[m]
τ:	period	[s]
f=1/ τ:	frequency	[Hz=1/s]
v:	velocity	[m/s]
	(vacuum: v=c=3*10^8 m/s)	



Our region of interest of electromagnetic spectrum: from UV field (a little less 0,4 microns in terms of wavelength) to the so-called "near infrared" (above 1 micron up to 10 micron of wavelength). Most of the first lasers are in the near infrared.

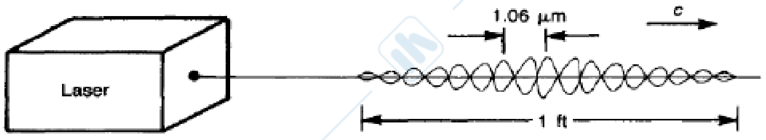
WAVE-PARTICLE DUALITY

Light = particles, photon:
- frequency
- phase
- amplitude (photons per unit area and time), intensity

photon energy $e_f = h \cdot f = h\dfrac{c}{\lambda}$

h: Planck constant
h= 6,63*10^{-34} Js

a)



1-J, 1.06-µm laser light pictured as a wave.

b)

1-J, 1.06-µm light pictured as photons.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

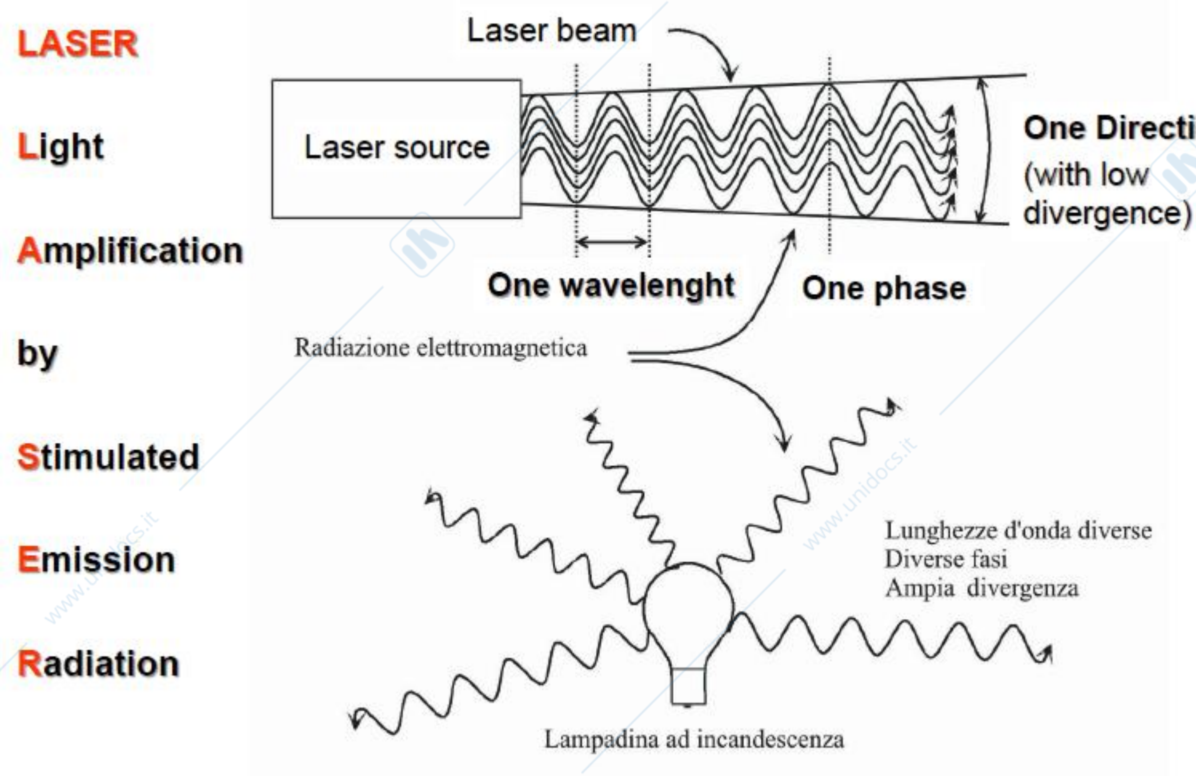
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

So far we have defined f and λ as properties of an electromagnetic wave because EM wave has this mathematical description/interpretation, but there is a dual interpretation of light: light can be seen as an electromagnetic wave or as particles; each particles is associated with a given mass and energy. According to the particle interpretation, a light beam is made of a lot of particles and each particle has a very precise energy quantum; that particle is calledd photon. A single photon will have the following energy:

$$e_{photon} = hf = h\frac{c}{\lambda}$$

Where h is the Planck constant. The higher the frequency (or the smaller the wavelength), the higher will be the energy associated to a photon. Smaller wavelength will go deeper into the material and will have higher energy, so the goal of the industry is to move the wavelength of the laser to go below 1 micron of wavelength.

INTRODUCTION TO LASER



It is true that laser is an electromagnetic field and can be seen as a beam of light, but it is a very special kind of light because it has several properties which makes it different from conventional light (conventional light is for example the light emitted by neon, lamp etc). LASER is an acronym: light amplification by stimulated emission radiation. Besides, laser has many different properties:

- if we compare the light emitted by a light bulb to a laser, we can see that the light bulb emits in all directions not necessarily with the same intensity in all directions (more intense in some portion of the solid angle), while laser sources emit in only

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

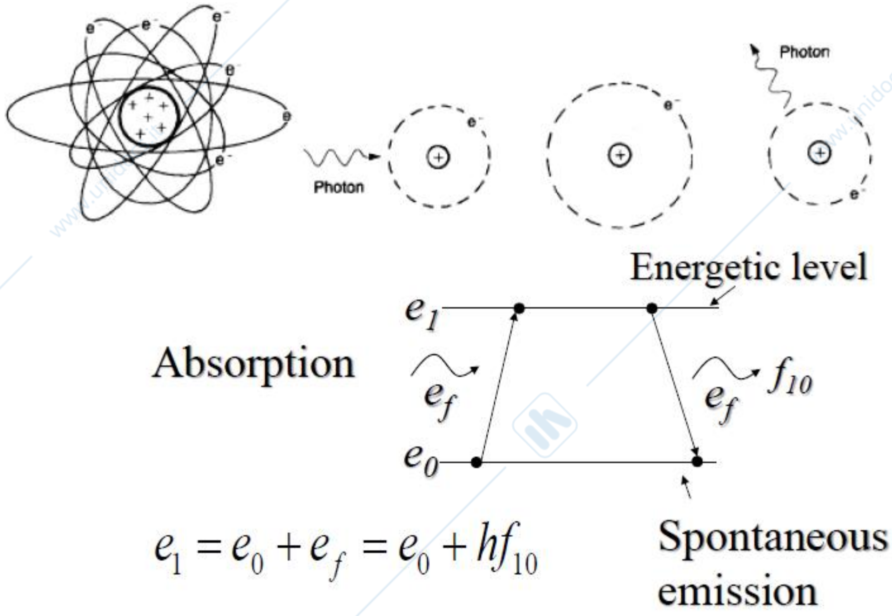
one direction with a little bit of divergence → we can focus our power on a given target (high power density), so this is a very important property.

- A second important property is that laser has only one wavelength: since A and α depend on the wavelength, we have a predictable laser-material interaction; on the contrary a typical light has a spectrum composed of several wavelength (for example the white light embeds the entire visible field).
- Finally, the waves of a laser have the same phase.

LIGHT AMPLIFICATION AND STIMULATED EMISSION

Both light amplification and stimulated emission can be obtained only if we have an active medium (only some materials can generate a laser beam). This active medium must be optically amplified or "pumped" in order to determine the stimulated emission.

Let's first of all see what is a spontaneous emission: we have an active medium and most of its atoms will be at ground level or equilibrium state (base energetic level), occasionally by accident some atoms can be excited at a higher energetic level. If we pump (pump= give energy to an active medium) an active medium we will bring many atoms at an excited level; if we have a crystal we can pump it with a flash light, this flash light will provide photons to the active medium. If the active medium will be able to absorb this energy, its atoms will be raised to an higher energetical level (its electron cloud/orbital will blow) for some time; then, after some time spontaneously the atoms decay back at the ground level. As a consequence of this decay, the photon that was absorbed by the atom is released (see the figure below).



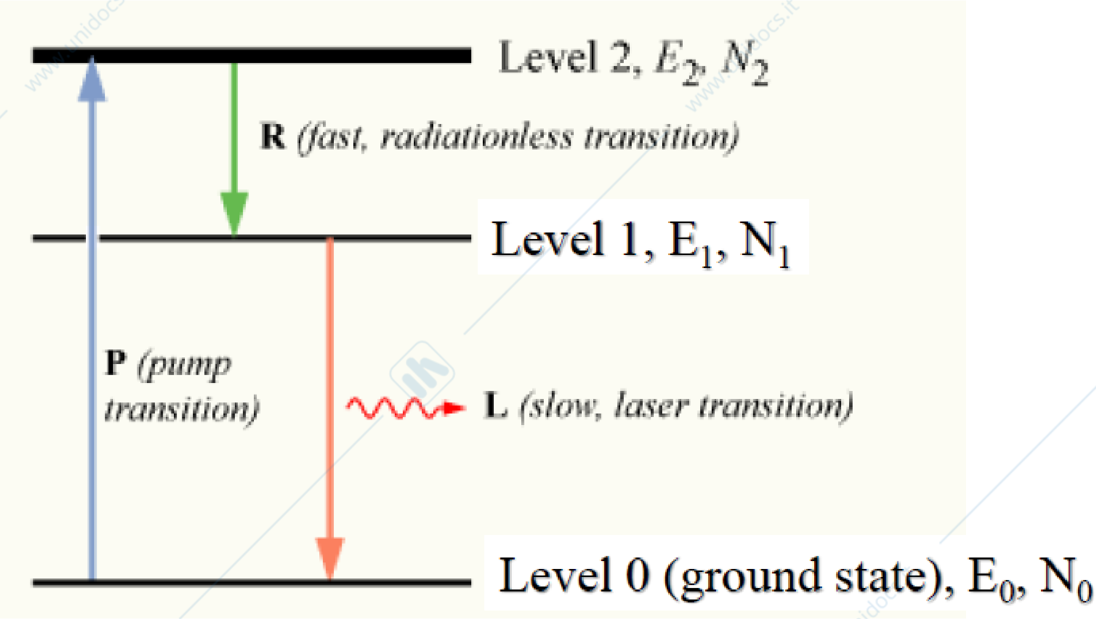
Notice from the figure above that the frequency of the photon emitted, and so its energy, depends on the absorbed energy ($e_1 - e_0$). With this mechanism of pumping the active medium by an external source of energy and waiting for the decay of the atoms and for the realeasing of energy, we are not producing a laser beam. We produce a laser light only

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

if the emission of the photons is not spontaneous but it is stimulated: immediately after we have provided the first photon, before decay takes place, we provide another photon. When we provide the first photon the atom raises to the higher energetical level, then the atom is hit again by another photon and at that moment it will emit both the photons at the same time→ we have provided 2 photons at 2 different times, but the atom will emit 2 photons in phase at the same time and with the same frequency → stimulated emission syncronizes the instant when the photons are emitted, it is also an amplification because we give to the atom 2 photons at different times and we receive back them in the same time (larger power at the output). But this is not a realistic behaviour (see after).

We cannot work with only 2 energetic levels (e_0 and e_1), most active media have at least 3 or more energetic levels. Let's see an example of an active medium with 3 energetic levels:

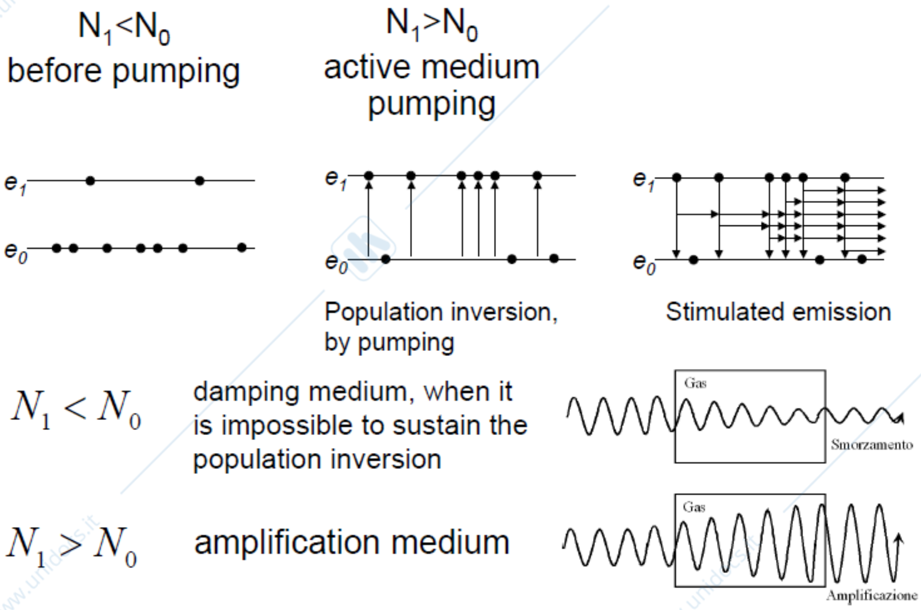


At the beginning all of the atoms are at the ground level, then:

- We turn on the energy source to pump the active medium→ pump transition from level 0 to level 2. In order to make this transition possible we must provide at least an amount of energy which is equal to $E_2 - E_0$.
- The spontaneous decay takes place at 2 stages: decay at level 1 and decay at level 0. If the second decay is slower than the first one and we continue to pump, statistically we will reach a condition where there are more atoms at level 1 than atoms at level 2. There are a few number of active media because we need to have such situation → only in that case we can intensify the total number of atoms that are at the first level.
- If we continue to pump, at some point we will have a number of atoms N_1 at level 1 which is not only larger than N_2 but it is also larger than N_0 → most of the active medium is excited. When N_1>N_0 we call this situation "population inversion". It is required necessary in order to sustain the laser at a stable emitted power.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



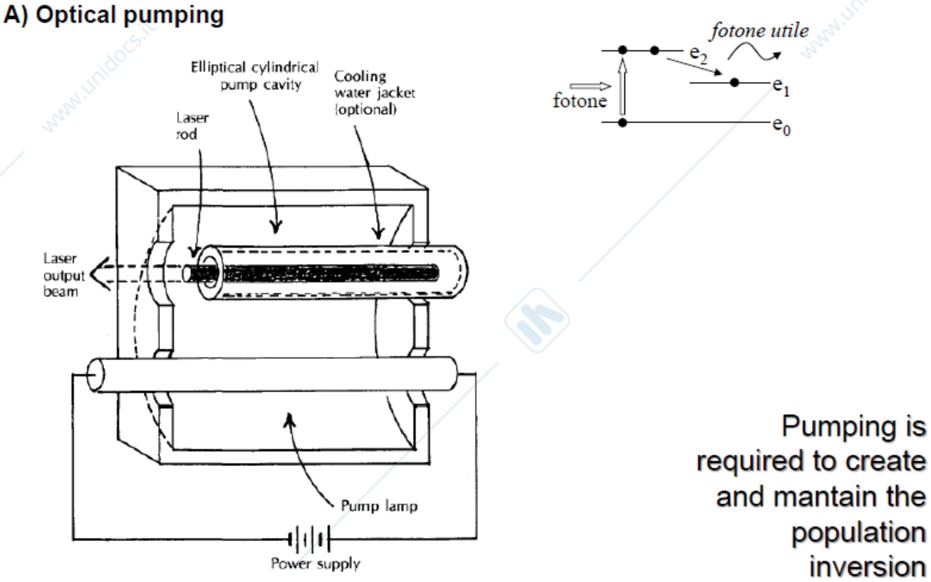
In real media so we give an energy $E_2 - E_0$ but it turns back only $E_1 - E_0$. So we have a quantum efficiency intrinsinc inherent to the medium:

$$\eta_{Q3} = \frac{E_1 - E_0}{E_2 - E_0}$$

This is the first reason why laser sources are highly energetic inefficient, producing the laser costs a lot of energy; but we can obtain a very high quality power because it can be focused in a very tiny spot.

PUMPING

The way we pump depends on our active medium. A typical example is the following:

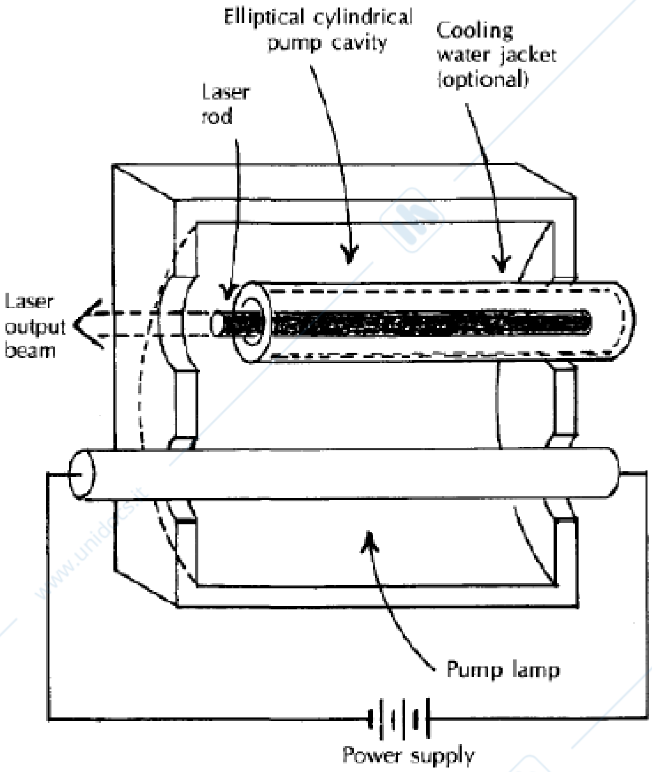


Pumping is required to create and mantain the population inversion

The active medium is a crystal rod and it can be pumped with a flash lamp. We need to have reflectors that focus the pumping light on to the rod; then, the laser light is emitted in

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

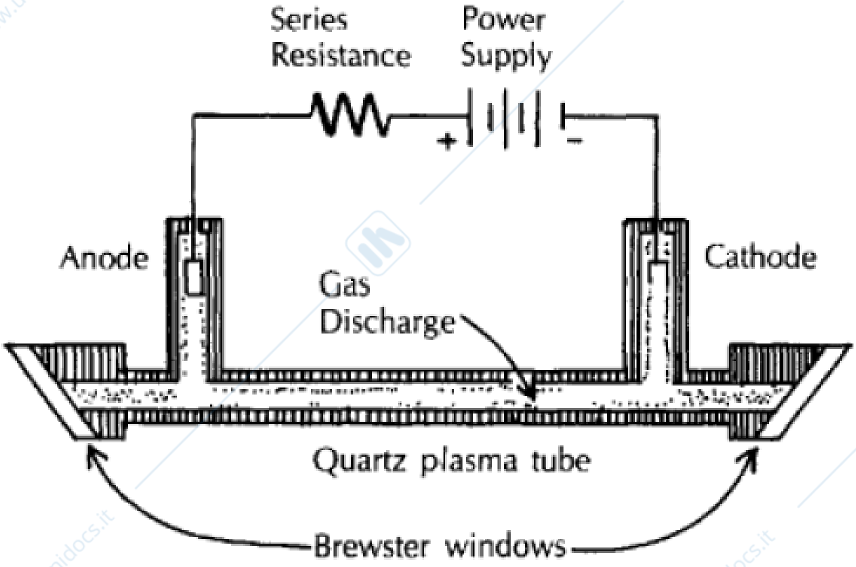
the axial direction. But, the atoms inside the crystal will be progressively excited and therefore will emit photons in random direcion; moreover, there will be not only external pumping but also internal pumping since one emitted photon will excite another internal atom and this process goes on. Since the photons are emitted in random direction, some of the laser rays will be oriented axially, a very tiny fraction of this power will be axial → total amount of power we are able to extract is a tiny fraction of the total amount of power we have given to the active medium. This is why we need to create, around our active medium, a so-called resonating cavity which is simply made of 2 mirrors: light is entrapped because there is the reflective mirror of the pumping lamp and also 2 axial mirrors. Axial rays will travel back and forth while rays which are not axial will escape, after some time of pumping most of the rays will be aligned on the direction of the resonating cavity. The 2 mirrors must be at a distance of a very precise multiple of the wavelength so that the waves are phased. Moreover, we need to extract this power→ one of the 2 mirrors must be partial reflective, usually less than 50% will go out.



The total efficiency of a laser is very little : quantum efficiency, rays not aligned which are dispersed, materials heat up, power generator has some efficiency and also the lamp (energy dissipation everywhere), partial reflective mirror. → 10-20% efficiency.

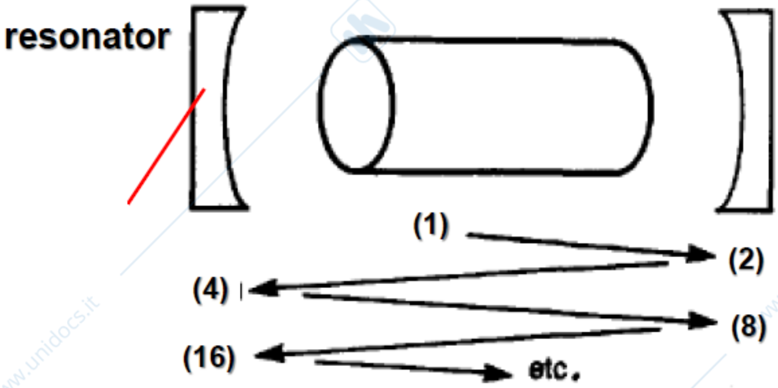
So, we need a resonating cavity and this concept applies also if we had a gas medium: in the case of a gas medium we don't use light to pump but we use a discharge arc between 2 electrodes (for a voltage difference). But the concept of having 2 mirrors is the same.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



Electrical discharge pumping can create a population inversion.

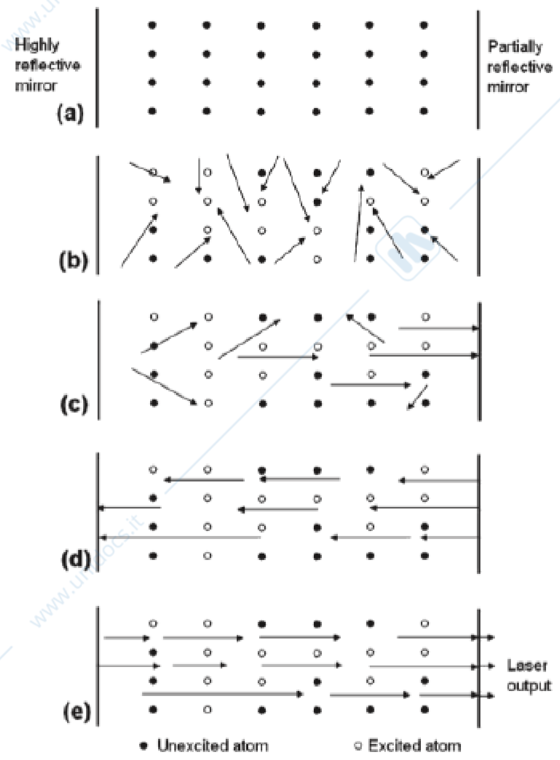
During the process described previously, rays travel back and forth and they hit the medium keeping the population inversion. So, the resontaing cavity actuates an amplification → rays travel back and forth, the population inversion is sustained and after some time the rays have mainly an axial direction (other directions are dispersed).



- For each photon emitted in the axial direction, 2 photons will be stimulated on the first path.
- After each reflection 2^n photons will be emitted

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



Schematic of amplification stages during operation:

(a) initial unexcited state (laser off)

(b) optical pumping resulting in excited state

(c) Beginning of stimulated emission

(d) amplification by stimulated emission

(e) continued amplification due to repeated reflection from the end mirrors resulting in subsequent laser output from one end of the mirror

Several sources of dissipation:

- Power supply.
- Pumping energy (lamps or voltage difference).
- Deposit energy: energy stored inside the resonating cavity, some of this energy will be lost because of temperature increase. We need to provide external cooling of the source otherwise the temperature will not be stable inside the resonating cavity. Inside the deposit energy we also have the quantum efficiency.
- Finally, efficiency due to the semi reflective mirror.

The total efficiency will be the product of these 4 efficiencies: at the end the total efficiency will be 2-20%. 20% is a good efficiency.

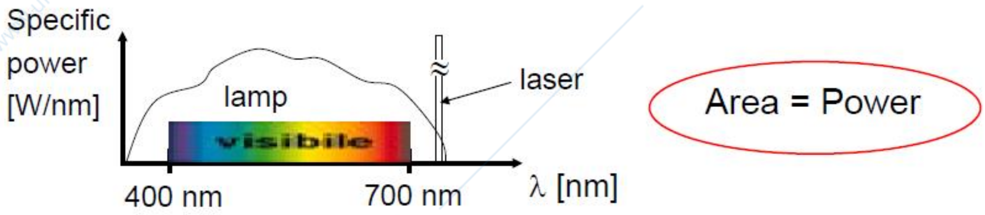
PROPERTIES OF LASER RADIATION

Thanks to amplification and to stimulated emission, the laser has some properties that the normal light does not have.

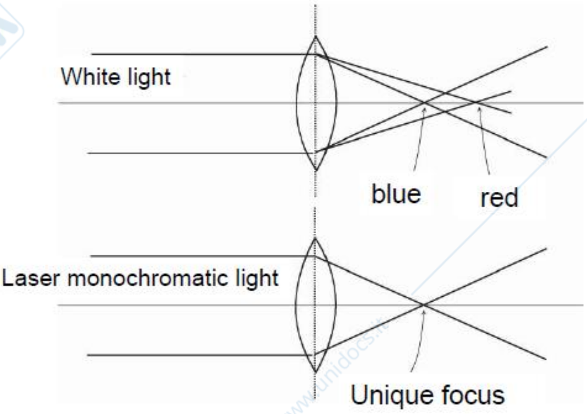
1. Monochromaticity → single wavelength. This is because during stimulated emission we obtain a photon and the frequency of that photon depends on the energetical difference between the 2 energetical levels. If we have a white light we can divide it, thanks to a prism, into the different colors, diffracting the wavelengths in different directions. If we do the same with a laser light, we will have diffraction (the direction of the laser will change) but we diffract in one single direction → only one wavelength. Why this property of the laser is very important?

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



Power spectrum



Let’s assume we have a focusing lens (figure above): the focusing lens must focus the laser (cilindric ray) in a very tiny spot. If we had a conventional white light, each different color will be focused in a different direction → the spot size would be much larger than the case of a laser beam, not only its diameter but also the depth. So, with white light we will have less energy density. Therefore, the focusing ability of a focusing lens will be much better with a laser light than with a conventional light.

2. Collimation: the laser beam will never be perfectly cilindrical, but there will be a certain angle of divergence θ. If you analyze the beam at the right of the focusing lens and at the left of the focusing lens, you can apply the following equation:

$$\theta d_0 = k\lambda$$

The equation says: in any location of the beam, even inside the resonating cavity, the product between divergence and minimum diameter will be constant. The constant is equal to the product between the wavelength and a factor which depends on the shape of the beam. Notice that the product at the left of the equal gives us information about the quality of the laser beam → small divergence and small minimum diameter are very good. In order to have small divergence and small diameter we need to have a good shape and a low wavelength → in that way we can collimate very well our laser beam.

3. Coherence in time and space

4. Brightness or Radiance

We have the definition of brightness for a spheric source of light, but we can ignore this definition because our source of light is not spherical but is more or less cylindrical. So, we can calculate the power density of the laser beam as:

$$I = \frac{P}{S}$$

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

Where P is the beam power and S is the beam section. Now we have 2 problems: is the laser cylindrical? Is the power density uniform over all the spot? Let's for the moment to assume that we have a cylindrical beam, is the density of photons uniform inside the beam? No, the density is not uniform, we can consider ourselves lucky if the photons are distributed with a Gaussian distribution or normal distribution. If the power is gaussian its k value is the minimum possible → this is the concept of shape of a beam.

In general, the profile of the power can be any, but the preferred profile would be a power profile which has a density that is maximum at the centre of the beam and that progressively decreases as we move out of the centre of the beam: this kind of profile can be modeled through a gaussian distribution. We can define the power density as a function of cartesian coordinates or as a function of cylindric coordinates, but if the distribution is axial symmetric, there is only the dependence on the radius of cylindric coordinates. The entire amount of power embedded in the laser beam in cartesian coordinates:

$$P = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} I(x,y)dxdy$$

Where I(x,y) is the distribution of the power density. Now we can calculate the amount of energy that the beam is able to transfer to the target:

$$Q = P\tau$$

Where τ is the time of interaction of the beam with the material. Now we can obtain the energy density dividing this energy for the surface of the beam:

$$F = \frac{Q}{S}$$

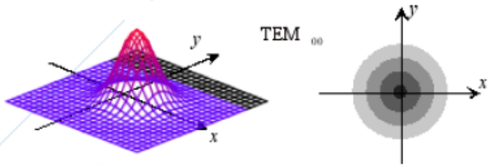
The power density I and the interaction time τ are the 2 most important process parameters that influence the technological transformation that we will perform on the material. By changing these 2 numbers we can perform different processes. Indeed for example τ incorporates the information of the travel speed of the torch, the higher is this speed the lower is τ.

In the figure below we can see how we can express mathematically the power density distribution of a Gaussian beam. Notice that I_0 is the value of the power density at the centre of the gaussian beam and r_0 is not the radius of the gaussian beam but it is a characteristic parameter of it. If we multiply the circular cross section of radius r_0 by I_0 we obtain the total integral of the power, it is a sort of equivalent radius of a beam with a rectangular distribution of the power density.

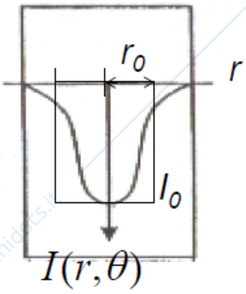
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

$$I(r,\theta) = I_0 e^{-\left(\frac{r}{r_0}\right)^2}$$



$$P = 2\pi \int_0^{+\infty} I_0 e^{-\left(\frac{r}{r_0}\right)^2} r\,dr = \pi I_0 r_0^2 \left[-e^{-\left(\frac{r}{r_0}\right)^2} \right]_0^{\infty} = \pi I_0 r_0^2$$

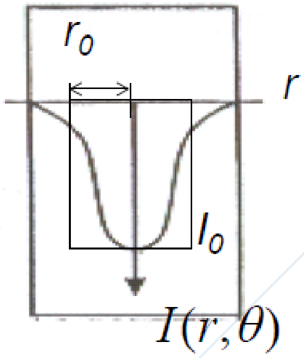


- Gaussian mode

Also called

- Fundamental mode
- Diffraction - limited mode
- TEM 00

r_0^2 is the variance of the distribution.



$$\sigma^2 = \frac{\int_0^{+\infty}\int_0^{2\pi} r^2 I(r,\theta)\,r\,d\theta\,dr}{\int_0^{+\infty}\int_0^{2\pi} I(r,\theta)\,r\,d\theta\,dr}$$

$$\sigma_G^2 = \frac{\pi r_0^4 I_0}{\pi r_0^2 I_0} = r_0^2$$

- r_0 is NOT the beam radius
- It is the “standard deviation” of the power density distribution function

Now we have to decide, for convention, how much the radius of the laser beam is. Indeed, our gaussian distribution extends to an infinity radius, but we can decide which is the radius over which the power density is negligible. Usually, for convention, the following value is used for the gaussian beam radius (r_G):

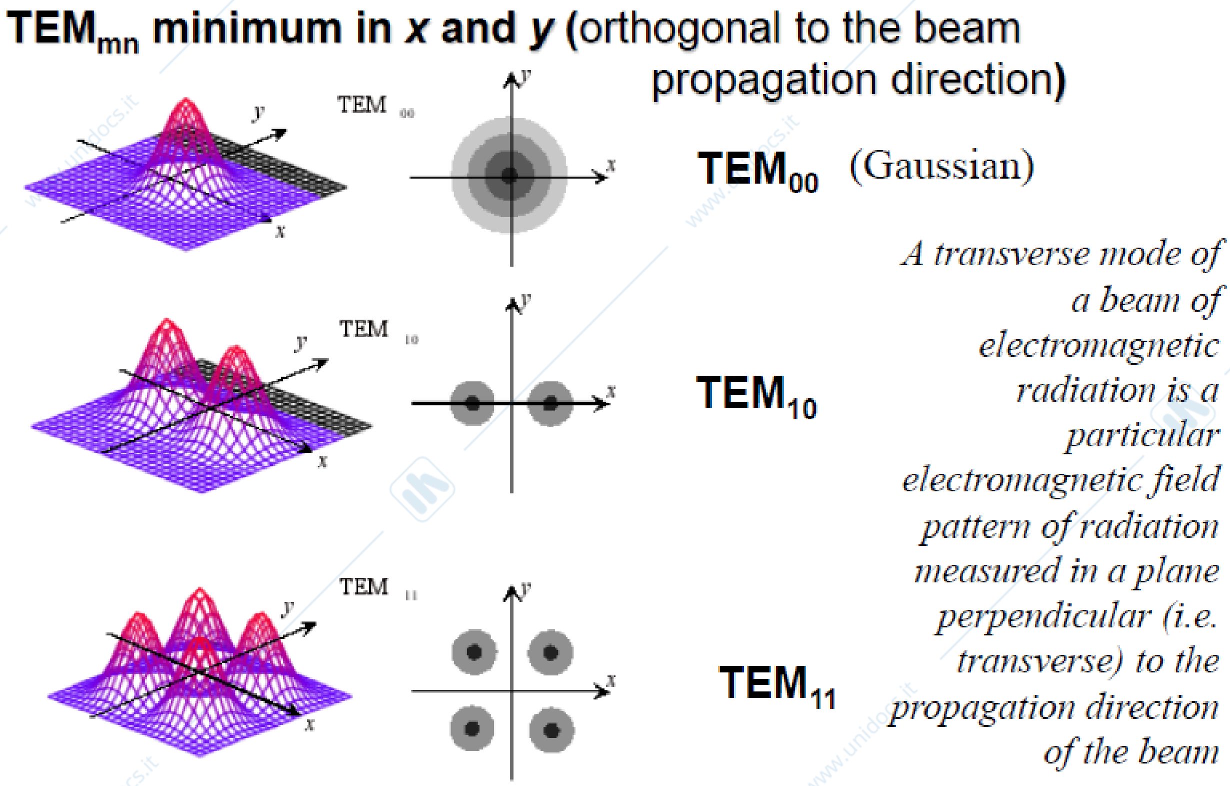
$$r_G = \sqrt{2} r_0$$

If you replace this number in the gaussian distribution you obtain that $I(r_G) = 0{,}135 I_0$, this means that the power inside our conventional beam is 86% of the total power. By convention we will have the laser beam only where the density power is higher than 0.,135 of the density power at the centre of the laser beam (peak of power density).

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

The Gaussian beam is not the only possibility (see figure below). In general we call the distribution of the power density "transverse electromagnetic wave", transverse because it concerns with the distribution of power density in a transverse cross section with respect to the propagation direction of the beam. The Gaussian beam is also called Gaussian transverse electromagnetic wave or TEM_{00}. If we have 2 peaks, this kind of beam is called TEM_{10}, or if we have 4 peaks the name is TEM_{11}; according to the active medium (type and shape) we can have different beam shapes → the shape of the beam is the distribution of its power density i.e. the TEM. Remember that k depends on the shape of the beam.

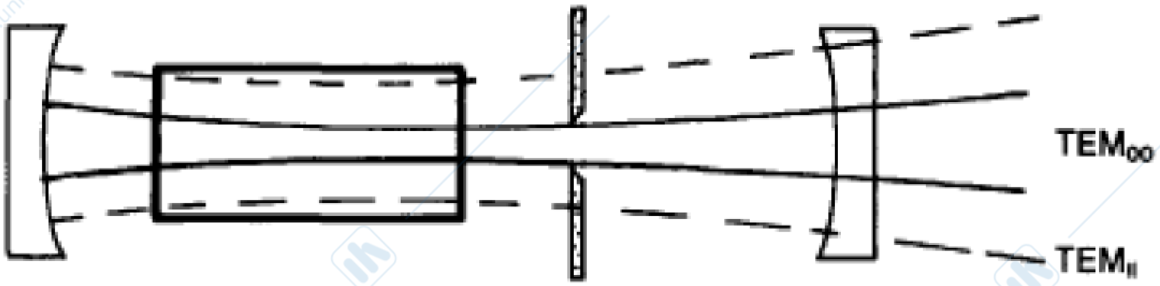


TEM_{mn} minimum in *x* and *y* (orthogonal to the beam propagation direction)

A transverse mode of a beam of electromagnetic radiation is a particular electromagnetic field pattern of radiation measured in a plane perpendicular (i.e. transverse) to the propagation direction of the beam

The shape of the beam is so important that we may want to "clean" the distribution in order to obtain a gaussian beam. So, we can perform beam shaping (figure below) inside the source by placing an optical filter, which is a hole which allows only the gaussian power to go through and will dissipate other transverse electromagnetic modes. It is possible because the gaussian beam is the more focused at the centre: it is relatively easy to dissipate the intensity which is away from the center. If we do that transformation, we obtain a beam which is sharper and better, it will focus the energy on a smaller region, it is also more precise and there will be less heat affected zone because the laser is able to concentrate the power on a narrower region (a lot of advantages). But we are decreasing the efficiency of the laser since we are reducing further more the power used. So, any beam shaping will deteriorate the efficiency of the beam. Remember that the gaussian beam is the one with the minimum diameter.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



- A transverse mode of a beam of electromagnetic radiation is an electromagnetic field pattern of radiation measured in a plane perpendicular (i.e. transverse) to the propagation direction.
- The TEM00 mode is smaller in diameter than any other transverse mode. Thus, if you place an aperture of the proper size inside the resonator, only the TEM00 mode will fit through it.
- Higher-order modes will be extinguished because the loss imposed on them by the aperture will be greater than the gain provided by the active medium.

Remember the equation that is valid for all the laser beams:

$$\theta d_0 = k\lambda$$

The Gaussian beam has the smallest possible k value because it has the smallest diameter and the smallest angle of divergence of all the beams. The k value for a Gaussian beam is equal to:

$$k_G = \frac{4}{\pi} = 1{,}27$$

And this is the smallest possible k value. The divergence is easy to obtain, it will be equal to:

$$\theta_G = \frac{4\lambda}{\pi d_0}$$

And also that will be the smallest possible. Now we can compare any other beam to the Gaussian beam: we can compare the k value of any other beam with the k value of the gaussian beam.

$$K = \frac{k_G}{k} = \frac{\theta_G}{\theta} = \frac{4}{\pi k} \leq 1$$

K is lower or equal to 1 because the k value of gaussian beam is the smallest, if K=1 we have a gaussian beam. This factor is called “beam propagation factor”. In the technical literature often you will not find K but:

$$M^2 = \frac{1}{K} \geq 1$$

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

This is called “beam propagation ratio”. M^2 is a quality parameter (it equivalent to K) of a laser source, when you buy a laser source the first thing that you look is the power, the second thing is the M^2. If M^2=1 you have a gaussian beam, if M^2 >>1 you don’t have a good shape of the beam. If M is more or less equal to 1, you can consider the laser beam to be cylindrical with a certain effective diameter. M^2 is used to find how much the laser diverges because:

$$\theta = \theta_G M^2$$

Another quality parameter is BPP (beam parameter product):

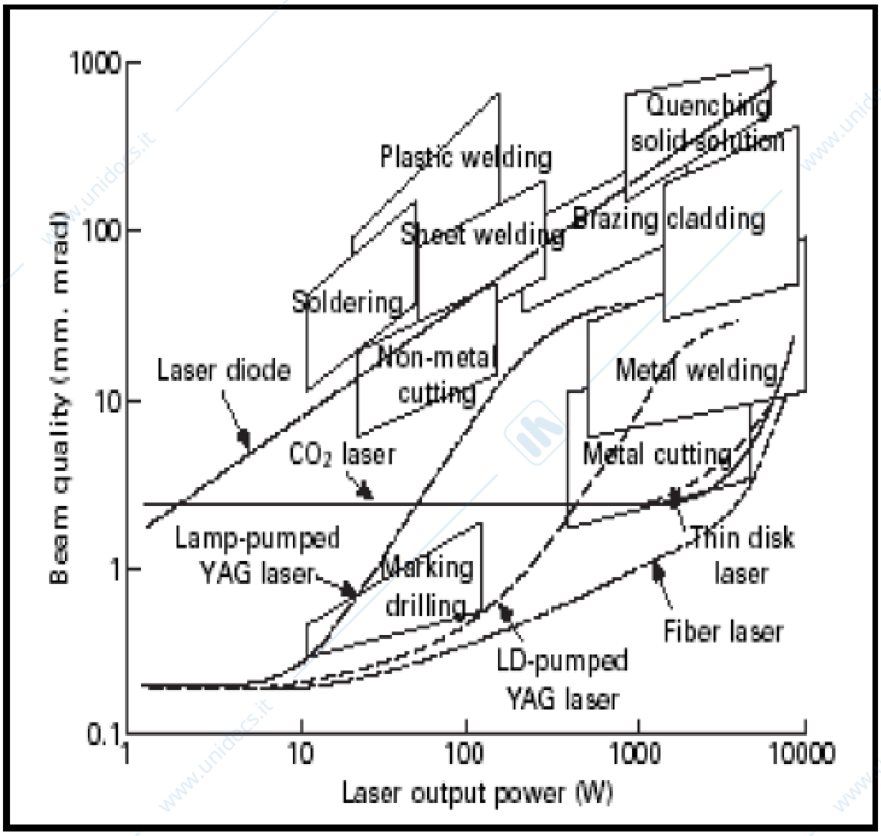
$$BPP = \frac{\theta d_0}{4} = \frac{1}{4} k\lambda = \frac{\lambda}{\pi K} = \frac{M^2}{\pi}\lambda$$

Notice that for the gaussian beam $M^2 = 1$:

$$BPP_G = \frac{\lambda}{\pi}$$

$$BPP = BPP_G M^2$$

The M^2 or the beam parameter product tell us how much we are able to reduce the diameter and the divergence of the beam → how much we are able to focus the power of the beam, to reduce the spot size and how so how much we are able to increase the power density. If we reduce θ and d_0 on the target, the same amount of power P can increase significantly the power density I. The quality of different kind of lasers given by different sources allow us to perform different operations (following graph).



www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

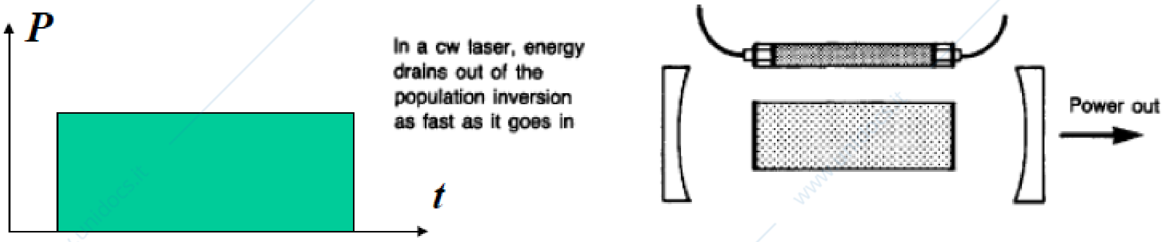
For example (figure above), for the diode laser, if we increase the laser output power, we are increasing the BPP. So, if we increase the power of the laser source we are decreasing the quality, it is easier to have good quality with lower power → if we increase the power we are heating more the source, we start to have thermal distorsions, dilatations, the quality tends to deteriorate. If we have good quality we can perform precison operations and power operations like marking drilling or cutting; if we have worse quality, we can do operations which require less power density.

We said that there are 2 variables which reduce the process: I and τ. We have said that:

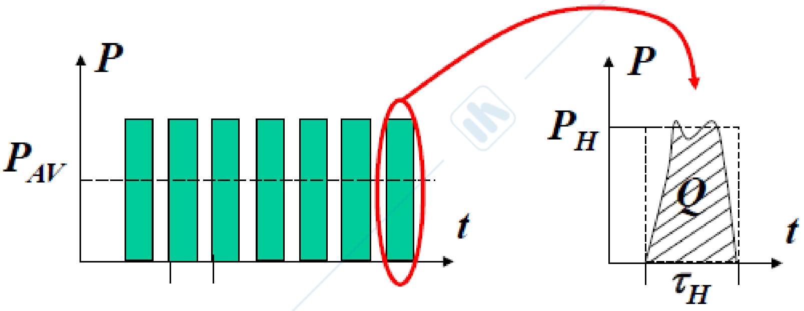
$$I = \frac{P}{S}$$

We have to intensify I and we are able to do that only if we are able to reduce S, but we are able to reduce S only if we are able to obtain a good quality of the beam. The other variable we can play with in order to move from one application to the other, is the interaction time τ. If we are able to give to the material the same amount of total energy in a reduced amount of time, we are increasing the power density and we are changing the way which laser interacts with the material.

How can we reduce the interaction time? We can reduce the interaction time mechanically going faster, but if we want to reduce the interaction time to a very small amount (microseconds, nanoseconds or even femtoseconds), the only way is to use pulse laser: we can pulse for example the energy directly from the laser source.



CW – Continuous Wave



PW – Pulsed Wave

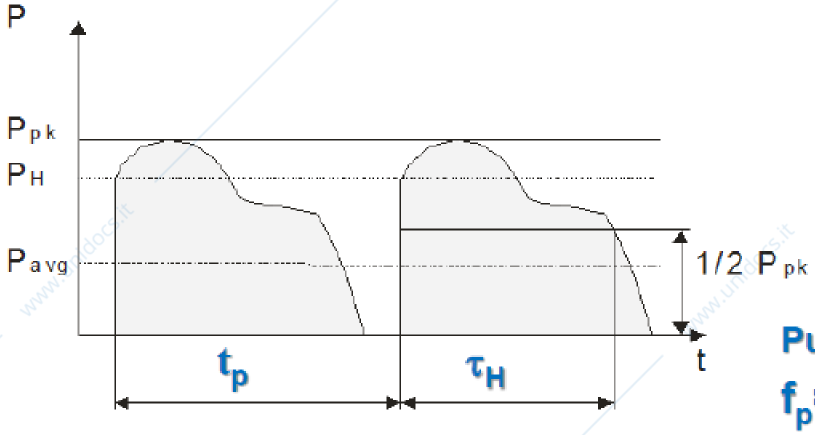
We increase the peak power for some time and we turn off the laser for some other time → alternate sequence of on and off. Practically the pulse won't be rectangular but will have

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

a certain shape (figure above). Out of the function of the pulse we have to identify some variables:

- Peak power: maximum power of the pulse
- Duration (how long is the pulse): we assume the end of the duration of the pulse when the power is come back to zero, or is it wiser to stop counting the time length of the interval before the power has come back to zero?



Pulse duration: τ_H

Pulse repetition frequency:

$f_p = p_{rf} = p_{rr} = 1/t_p$

Peak power $P_{pk} = \max_{0<t<\tau_H} P(t)$

Average pulse power $P_H = \frac{1}{\tau_H}\int_0^{\tau_H} P(t)\,dt$

Total pulse energy $Q = \int_0^{\tau_H} P(t)\,dt = \tau_H P_H$

Average power $P_{av} = f_p Q = f_p \tau_H P_H$

duty cycle $\delta = \frac{\tau_H}{\tau_p} = f_p \tau_H$

We decide to stop counting the duration of the interaction when the power of the pulse is ½ of the peak of power. The parameters which characterize the pulse are:

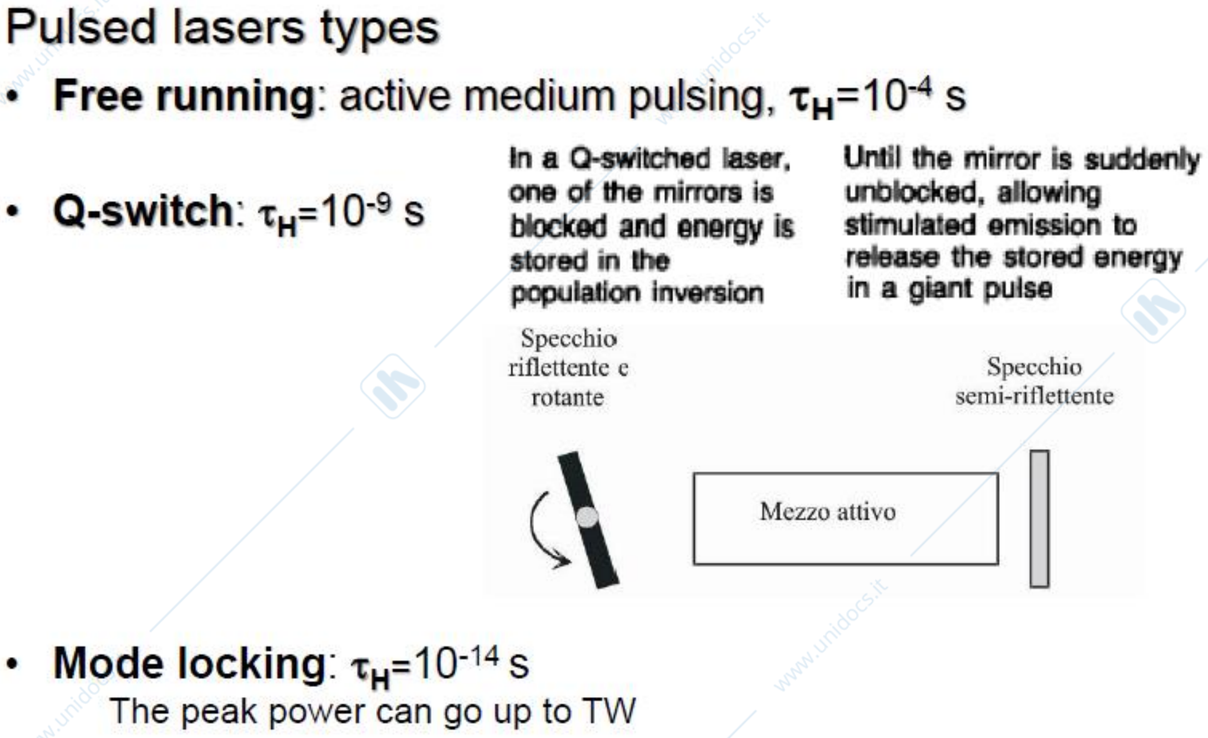
- Peak power
- Average power: average power considering the entire cycle on-off
- Actual interaction time τ_H or pulse duration
- t_p: range of time between the beginning of a pulse and the beginning of the next pulse, between the 2 pulses there is always an off-time.
- Pulse frequency $f_p = \frac{1}{t_p}$
- Duty cycle $\delta = \frac{\tau_H}{t_p}$. If we are in the case of continuous wave the duty cycle is 1, while if we are going towards a pulsed wave we are reducing the value of the duty cycle.
- Average pulse power P_H is the average power of the pulse considering only the interaction time τ_H.
- Total pulse energy Q: it is the total energy emitted in the pulse duration. Notice that because of how P_H is defined, we can write $Q = \tau_H P_H$

We can make pulsing in three ways:

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

- We do nothing: the source is naturally pulsed because we are for example sustain the active medium with a flash light which is not continuous, so the power output of the laser source will be not continuous, it might be pulsed. These lasers are called "free running laser", in that case we can pulse for a time duration of 10^{-4} seconds.
- Q-switch: mechanical pulsing of the energy by using for instance rotating mirrors, there is a rotating mirror inside the source that makes the beam go out for some time and reflects the beam inside the source itself for some other time. In that case we might lose some power, while on the contrary in free running and in mode locking we are not losing any efficiency, we are only storing the energy inside the resonating cavity while the power is not emitted.
- Mode locking: optical interference techniques inside the source.



Pulsed lasers types

- **Free running**: active medium pulsing, $\tau_H = 10^{-4}$ s
- **Q-switch**: $\tau_H = 10^{-9}$ s

In a Q-switched laser, one of the mirrors is blocked and energy is stored in the population inversion

Until the mirror is suddenly unblocked, allowing stimulated emission to release the stored energy in a giant pulse

- **Mode locking**: $\tau_H = 10^{-14}$ s
  The peak power can go up to TW

If we are able to maintain Q constant and to recude τ_H, we are increasing P_H and also the peak power. This is the reason why we use pulse power: by reducing significantly the interaction time we are increasing the pulse power. Moreover, if we reduce the interaction time to a very incredible small time, there is no time for the heat to be transferred because heat conduction inside the material needs time. Practically this is a temporal way of focusing the power, we remove material without dissipating it in the surrounding regions, this is the main motivation why it was reduced time.

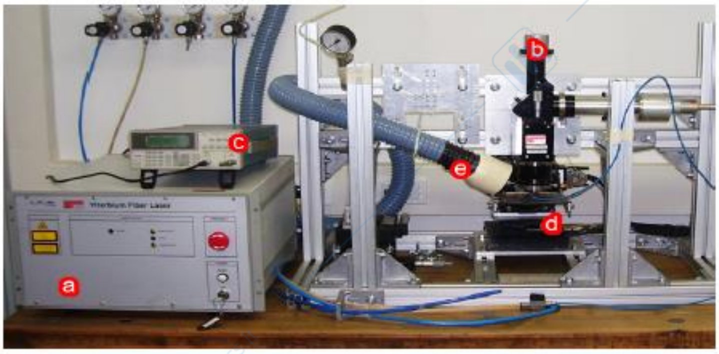
Let's see a numerical example: notice that if we reduce the interaction time, we can achieve a value for P_H which is very high although we have a laser which is not so powerful. A power of 12GW is able to brake directly the atomic bonds, there is no heat conduction but only an electromagnetic field which interacts with the structure of the material and removes the material. We told that laser is a thermal process, but if we are able to apply

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

such as huge amount of energy in a very short time, laser is not hot anymore but it is a process which interacts directly with the structure of matter. The process which uses these very short interaction times is called "laser ablation" → we are able to remove the material without heat.

Maximum average power	P_{av}	50 W
Wavelength	$\lambda=$	1064 nm
Pulse repetition rate (PRR)	f_p	20-80 kHz
Pump current %		10-100%
Pulse energy range	Q=	0.5-1.2 mJ
M²		1.7
Collimated beam diameter		5.9 mm
Focal length		60 mm
Beam waist diameter		23µm



$$\tau_H = 100\,ns \quad \rightarrow \quad P_H = \frac{Q}{\tau_H} = \frac{1.2\cdot 10^{-3}}{100\cdot 10^{-9}}\frac{J}{s} = \frac{1.2\cdot 10^{-3}}{10^{-7}} = 1.2\cdot 10^{4} = 12kW$$

$$\tau_H = 100\,fs \quad \rightarrow \quad P_H = \frac{Q}{\tau_H} = \frac{1.2\cdot 10^{-3}}{100\cdot 10^{-15}}\frac{J}{s} = \frac{1.2\cdot 10^{-3}}{10^{-13}} = 1.2\cdot 10^{10} = 12gigaW$$

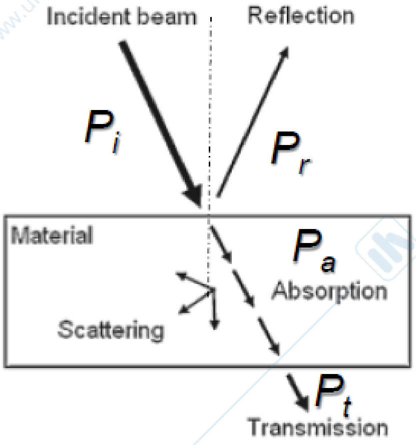
With the same total energy expenditure, the average pulse power is much larger in pulsed lasers

LASER-MATERIAL INTERACTION AND CUTTING APPLICATIONS

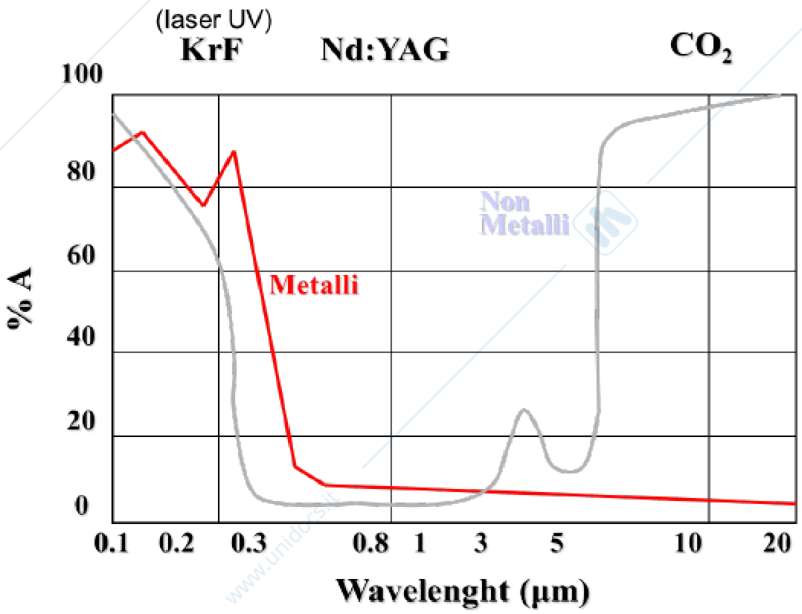
The interaction with laser beam and material depends on several factors, it depends for example the incident power, on the time interaction but also on the material itself (the surface and the nature of the material). Some materials are transparent, others are reflective, and it is important to define the coefficient A (absorption coefficient) in order to understand if a material can be machined with the laser process or not. Moreover, it is even imporant to define if the material is transparent or not, so it is imporant to define, as we have already said previously, the skin thickness of the material. If the skin thickness s is large enough, we can consider that the power transmitted (power that has not been dissipated or reflected) is almost zero. We want A as large as possible so that the material dissipates rapidly all the incident power (it absorbs power). The value of A depends on the material but also on the wavelength of the laser (figure below). If λ is little the laser is absorbed better, but unfortunately this not happens in industry. In the graph below remember that there are the absorption coefficients at room temperature.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



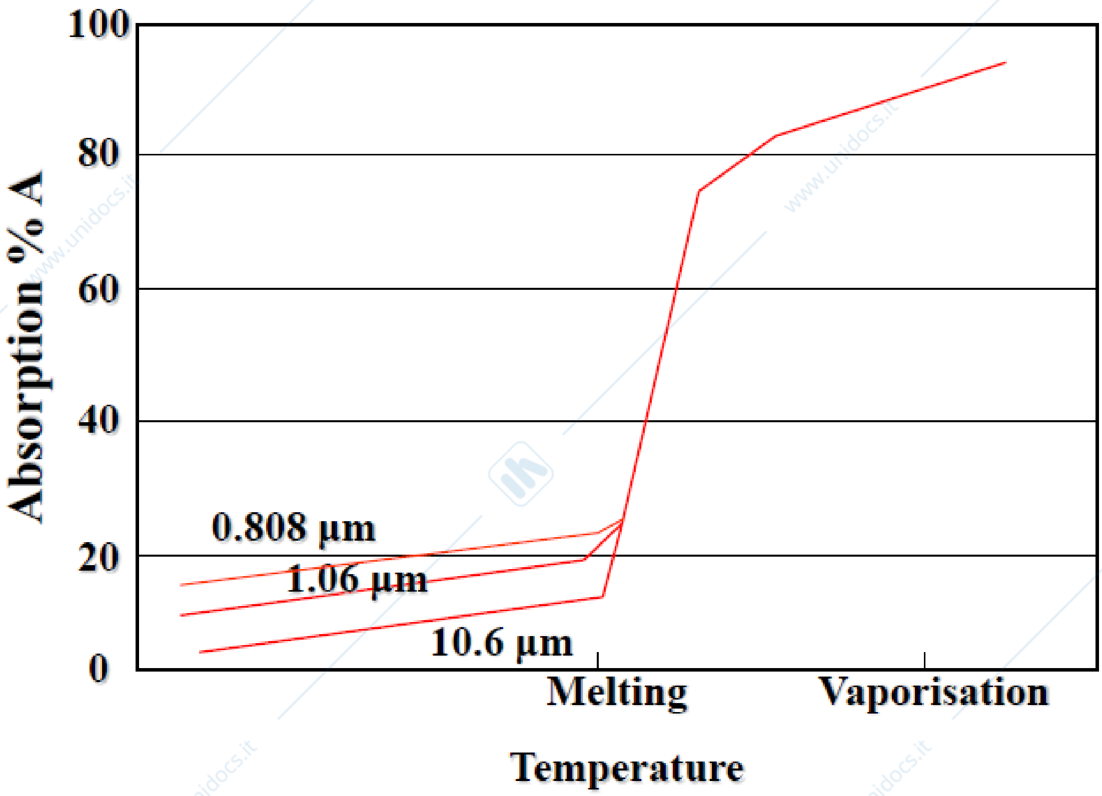
$$P_i = P_a + P_r$$
$$P_r = RP_i$$
$$P_a = (1-R)P_i = AP_i$$
$$A + R = 1$$



If sheet thickness t_0 > skin thickness s

$P_t \approx 0$

But the good thing is that if we turn on the laser and we wait for a while, sooner or later at least the outer surface of the material will approach the melting temperature → liquid state. As soon as the liquid forms on the top of the surface, immediately the A jumps (figure below).



www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

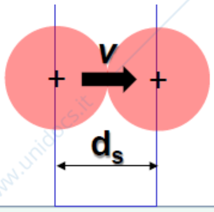
So, if we increase the temperature of the metal we are slowly increasing the absorption coefficient, but if we reach the meltimg temperature we have a drastic increase of A, and it is even better if we reach the vaporisation temperature, it usually happens in industry. In that case A is so high that we can assume it equal to 1. Therefore, we have eliminated the problem of A if we wait for some time that the material reaches the melting point.

Figure below: the interaction time depends on the spot size and on the travel velocity of the laser. Remember that d_s is not necessarily equal to d_0 which is the minimum diameter achieved in the laser. The input of the heat equation is the absorbed heat flow, it is simply the incident power density times the absorption coefficient.

$$\tau = \frac{d_s}{\mathrm{v}}$$

τ Interaction time

v Laser beam velocity



$$q_s'' = \frac{P_a}{S} = \frac{4}{\pi}\frac{A \cdot P_i}{d_s^2} = A \cdot I_i$$

q_s'' Absorbed heat flow on the surface

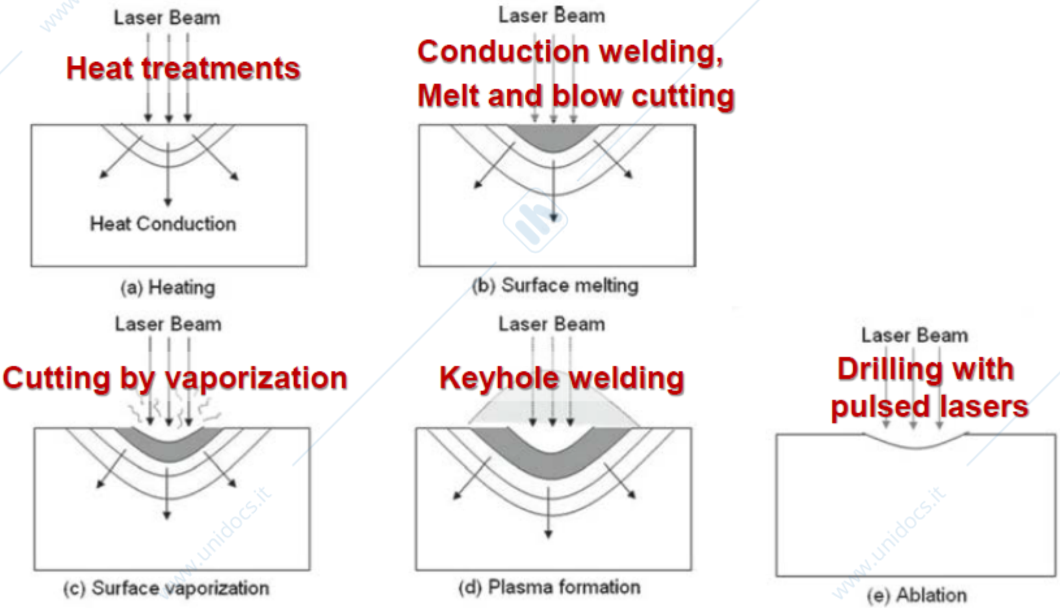
I Power density [W/m^2]

$$F_a = A \cdot I_i \cdot \tau$$

F_a Absorbed energy density [J/m^2]

By changing I and τ we can play different interaction phenomena, while we cannot act a lot on A because it depends mostly on the material and on its surface.

I and ***τ*** are basic parameters for the interaction phenomena:



www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

Let’s explain the different processes obtainable with laser:

a) At the beginning of the process the laser heats up the material and heat transmits inside the material through conduction. Thus, the first process that we can do is a heat treatment, during this process A can be even so much low because of the surface remains solid.

b) If we continue the treatment in the same point, a film of liquid will be created since the material will melt. The film of liquid causes the absorption coefficient increase up to values as 80%. In that situation we can do 2 types of process: conduction welding (melting pool is created by heat conduction inside the material) and cutting by melt and blow.

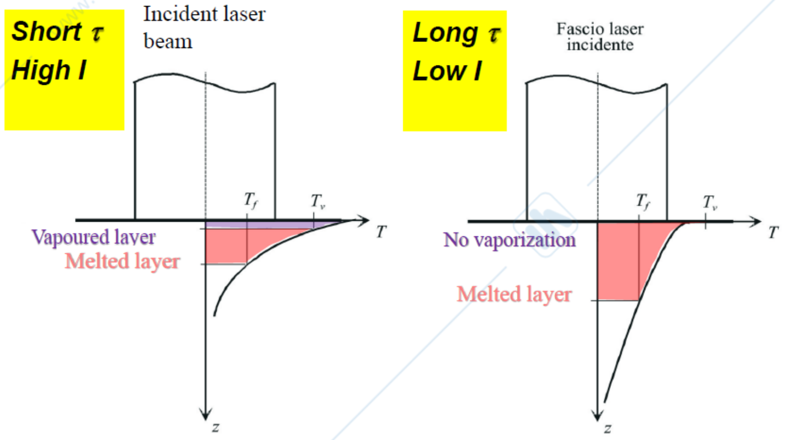
c) If we continue the treatment in the same point (we increase the interaction time), at a certain moment the liquid will vaporize; when surface vaporization occurs, the value of A increases up to 100%. How long it takes for going from condition “a” to condition “c” depends on the material, for a given laser. In that case we can do cutting by vaporization.

d) If liquid and vapor are overheated, we will enter a new condition: the vapor will transform itself into plasma (superheated gas). Plasma behaves in a completely different way and also the heat conduction in the material changes → the direction of heat conduction becomes vertical; as a consequence heated regions will be deeper and less wide than before. Now we can do keyhole welding, “keyhole” means that there is a column of plasma inside the material.

e) For a given material, we can directly go on vaporization or material removal without intermediate phases; in that case we talk about “ablation”. One example of process made through ablation is the ablation of the skin for aesthetic parts.

Remember that we can obtain conditions from “a” to “e” varying the values for “I” and “τ”. An example in the figure below.

I and τ are basic parameters for the interaction phenomena:



We are interested especially in 2 processes:

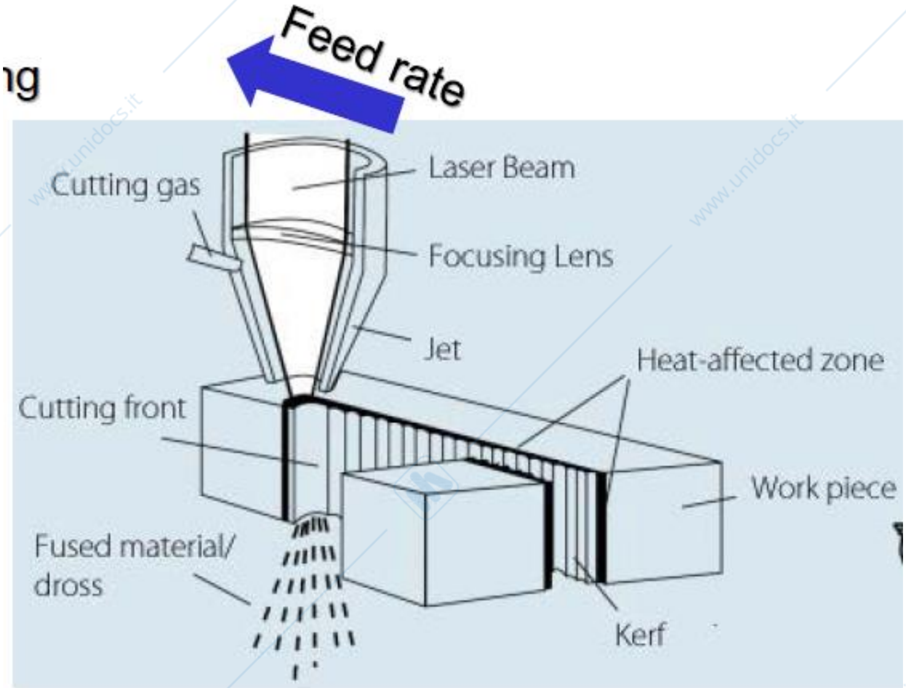
- Material removal by cutting.
- Joining by welding.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

METHODS OF LASER CUTTING

In general, when cutting with the laser, we obtain a cutting kerf and we would like to have the same target features already said for the waterjet. The only difference is that now there will be also the heat affected zone (HAZ) because of the heat will flow inside part of the adjacent material by conduction. For cutting we need a relative movement between the workpiece and the torch containing the laser, the movement can be given to the torch or to the workpiece depending on the type of laser mainly. The laser beam must be focused in a little spot, the diameter of the spot is more or less 1 mm.



Three fundamental methods for cutting are:

- Fusion:
  - Melt and blow: in this type of process at least the surface of the material is melted, remember that it is not forbidden to have some vaporization or formation of plasma. Moreover, we need to blow away the material from below the workpiece, this ejected material is called “dross” and usually is solid because solidifies very rapidly. The only way we have to eject the material is by using a cutting gas that is blown inside the laser beam from the sides of the torch. On the sides of the laser torch there are some nozzles (restrictions), here the high pressure of the gas is converted into kinetic energy. Then, when the gas goes out from the torch, it transmits its kinetic energy to the dross that is pushed away from the cutting kerf. In this process the gas is a non reactive gas as for example argon.
  - Reactive melting: it is the same of melt and blow, but here the gas is reactive, for example oxygen or air are used. The active gas will oxidize the material: this exothermic reaction will provide additional heat so that the action of the laser is helped by this chemical reaction. As a consequence, the feed rate can be increased

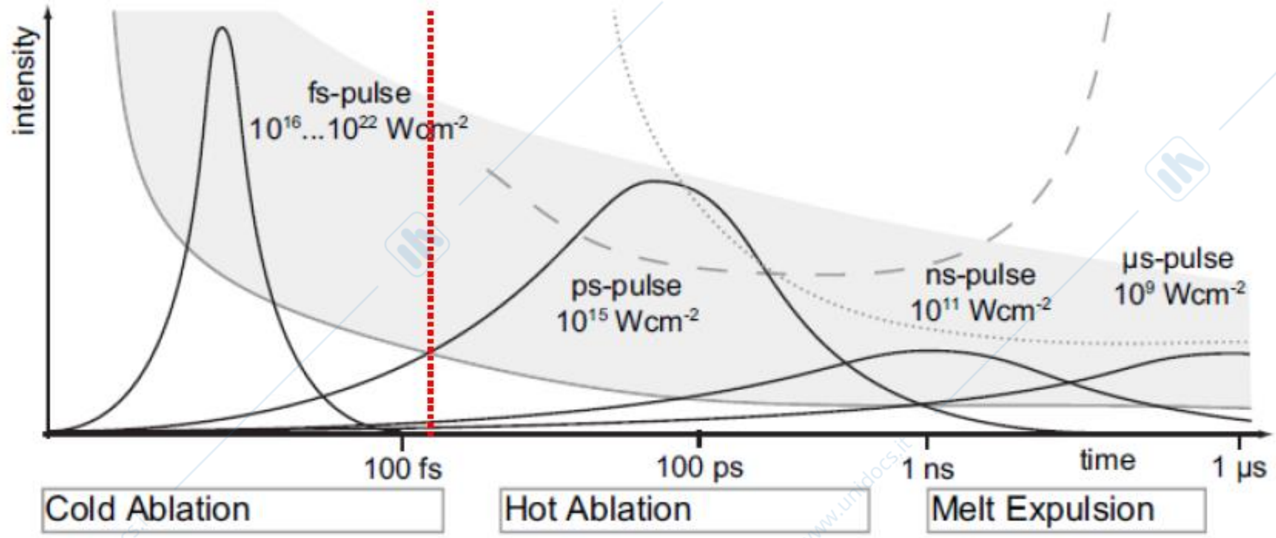
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

because the heating up will be faster. Obviously, reactive melting isn't used for example with stainless steel because in that case the Chromium oxide cools down very quickly after its formation and will increase the cutting time.

- Vaporization: in that case material is vaporized and is ejected by vaporization. In general, we can do this type of process when vaporization is very rapid and the workpiece is very thin; again a gas can be used but now the material will be dispersed in the system and not ejected from the below.
  - High surface quality
  - High energy
- Ablation and cold cutting: in that case the material is removed without melting the material, it is a cold cutting for this reason.

CUTTING BY ABLATION



We can do material removal by ablation only by pulsing the laser, so by reducing the interaction time. If we do pulsing below 1ps, there is no time for the electrons to relax before another pulse starts → this means that there is no time for heat conduction, atomic bonds are broken without heating the material. In practice, there is no HAZ because the removal is extremely localized. This is the reason why the process with very low pulse time is called "cold ablation". While if we use a higher pulse time, some heating is created and we move rightwards in the graph above.

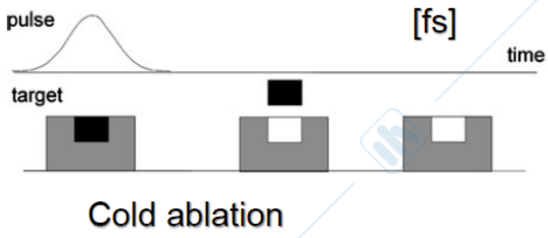
Now, when does cold ablation occur? In general we assume that cold ablation occurs when the pulse time is so small that the thermal distance (or diffusion depth) $D = \sqrt{4\alpha\tau}$ is smaller than 2 times the skin thickness:

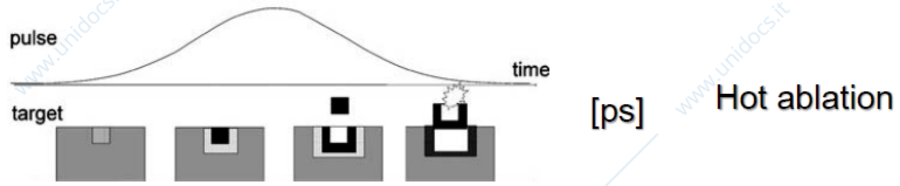
$$D \ll 2s$$

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

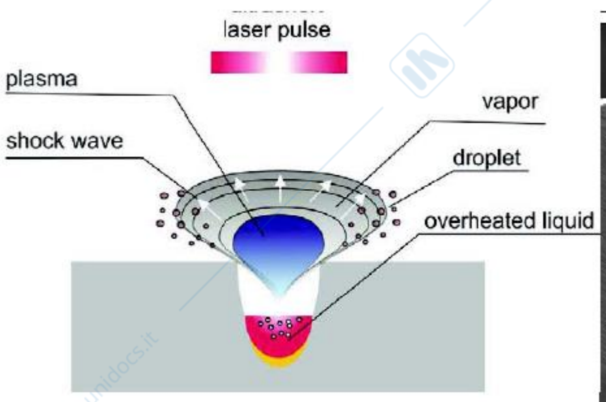
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

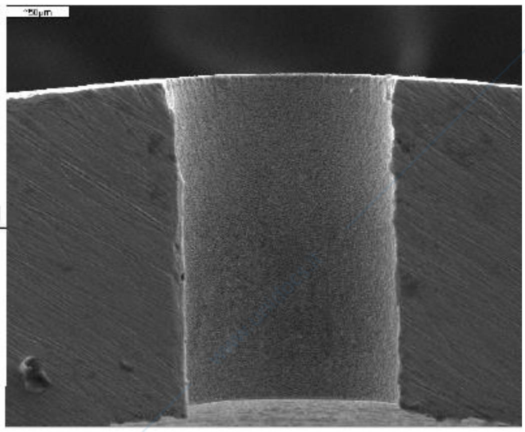
In the figure below, a schematic which explains the difference between cold ablation and hot ablation.





HOT ABLATION





4 phases are present at the same time: liquid droplets, overheated liquid, vapor and plasma (ionized high temp. vapor)

We can get rid of overheated liquid with a preliminary through hole

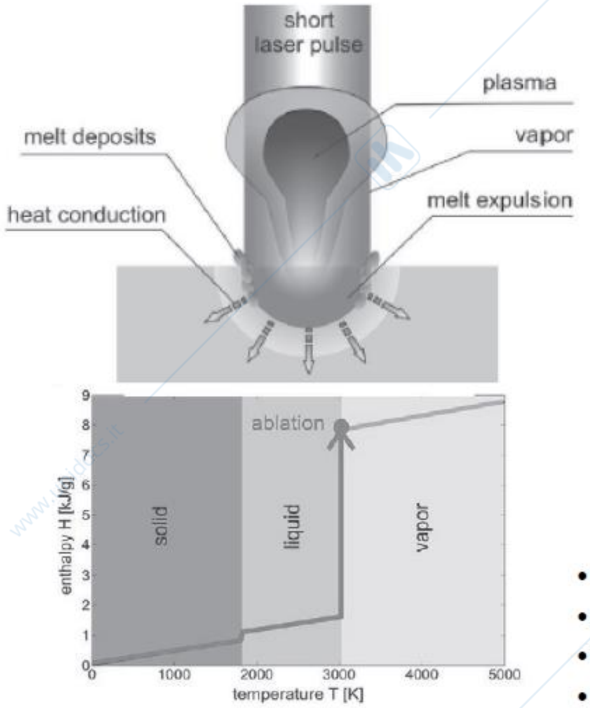
- Ablation by shock wave generated by pressure of vapor and plasma
- Ionized material
- Phase explosion
- Negligible HAZ

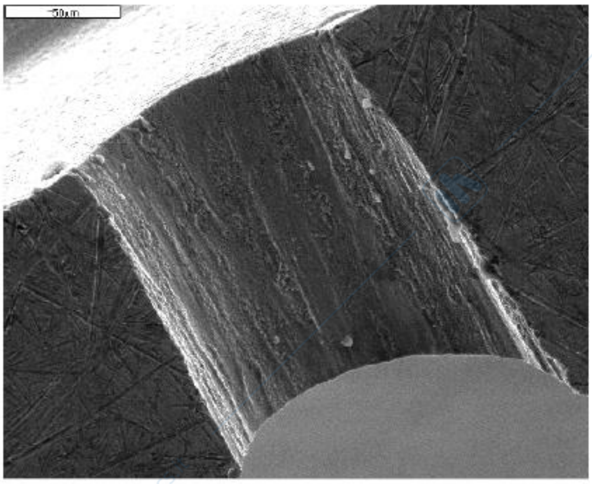
In the figure above there is an example of a hole generated by hot ablation. In the schematic we can see the different phases: liquid overheated, vapor, plasma and liquid material droplets. In that case the creation of plasma causes mechanical shock waves which eject the material. The heat affected zone is present but is practically negligible.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

MELT EXPULSION

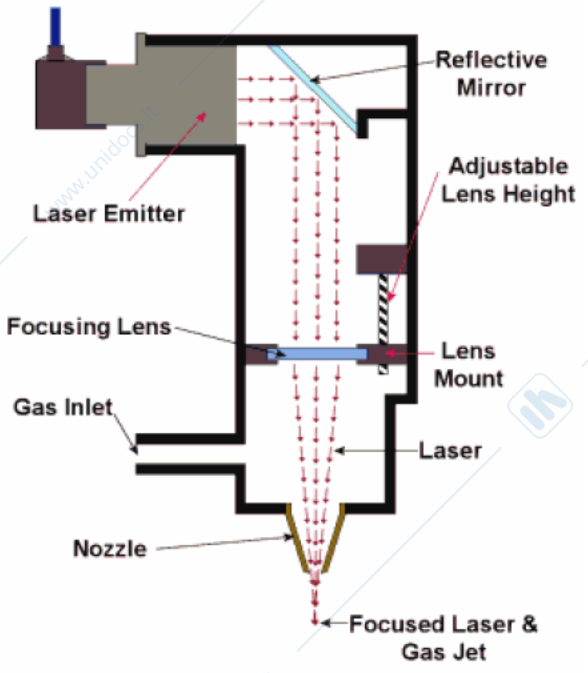




- Evaporation and melt expulsion
- energy absorbed at the free surface
- Plasma formation
- Internal striation

Also here the pressure created by the plasma is enough to blow out the material. In that case there is a higher heat affected zone and the surface is a little bit more rough than before. Therefore, tolerances worsen as the duration of the pulse increases.

LASER CUTTING HEAD



- ***focusing system***
  - GaAs or ZnSe for CO_2
  - quarz for Nd:YAG
- ***nozzle***
  - 0.5–2 mm metals
  - 1-3 mm non metals
  - 0.2-2 MPa gas pressure
    - *blow away*
    - *protection*
    - *cooling*
    - *energy (oxidation reaction)*

In the figure above, an example of a laser cutting torch, used for example for melt and blow process. Originally melt and blow was mostly done with CO2 laser sources which

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

produce a laser with a wavelength of 10.6 microns. A laser with such wavelength cannot be transmitted inside fiber glass, so they can only be transmitted with reflective mirrors. While, using a solid state laser source (as quartz or rubin), the wavelength will be less and it can be transmitted by fiber glass. In the case of transmission with mirrors, they can be rotated/moved to adjust the laser but the torch must remain still because otherwise the precision would be compromised. Therefore, with CO2 laser source the workpiece must be moved in order to perform the process. While with a source as Nd:YAG I can move the torch because laser is transmitted by fiber glass. In the figure we can see some values for the diameter of the nozzle and for the gas pressure. The functions of the gas are several:

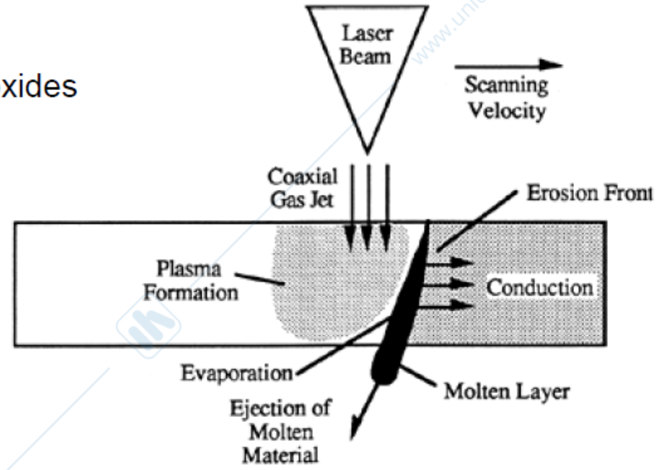
- It blows away the material: the high pressure of the gas is converted into kinetic energy that will be trasmitted to the material for the removal.
- It protects the mirrors: the material during the process is melted and vaporized at very high temperatures, so the gas will surround mirrors at high pressure avoiding the inlet of vapor and of heat inside the torch protecting in that way the mirrors.
- It cools down the cutting head maintaining it at retalively low temperatures.
- It can contribute to the cutting process if an active gas is used, in that case we talk about reactive melting.

Moreover, notice that the "Lens Mount" can be moved up and down by a mechanism in order to regulate the spot size on the workpiece.

FUSION CUTTING

Metallic alloys cutting methods:

- **reactive fusion cutting**
  - high thickness
  - high productivity
  - cutting edge with oxides
  - only some alloys
- **melt and blow**
  - low thickness (<10 mm)
  - high quality
  - low velocity
  - Need of (costly) inert gas
    - N_2, Ar, He



In the figure above are listed the main features of the 2 types of fusion cutting. Remember that there are 2 velocities in this process (as in water jet):

- The material removal rate, it is a vertical velocity of removal.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

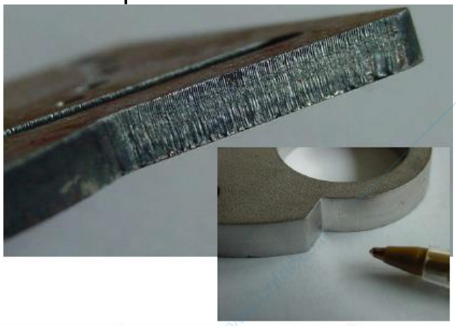
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

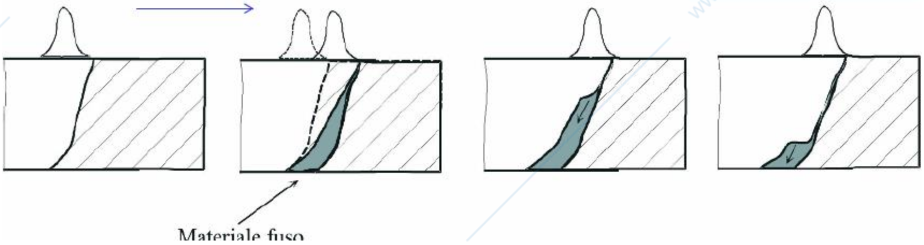
- The transverse speed, it is the speed of the torch.

In the case of laser, conversely from water-jet, the risk of uncutting is very low. Simple melt and blow we should limit the thickness, we have a better quality but we should go a little bit slower, we need inert gas which protects the material from oxidation (nitrogen and argon are expensive, more expensive than air and oxygen). So the second one is more expensive because we need a more expensive gas and because we go slower; but we have a better quality because of oxides are not present.

Forming of striations

- step theory
  - the critical droplet size causing the melt to pulsate in size before it can be blown free

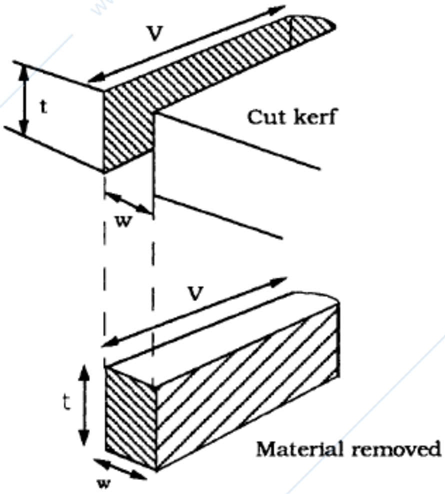




The cutting progression is backward oriented because the combination of the 2 velocities, but this does not fully explain the striation. The scientific community is not sure about it, there are some theories that explains the reason of striation.

$$A \cdot P = w \cdot t \cdot v \cdot \rho \left\{ c_p \left(T_f - T_a \right) + L_f + m' L_v \right\}$$

where:
P = Incident power (W)
w = Average kerf width (m)
t = Thickness (m)
v = Cutting speed (m/s)
m' = Fraction of melt vaporized
L_f = Latent heat of fusion (J/kg)
L_v = Latent heat of vaporization (J/kgK)
T_f = Fusion temperature (K)
T_a=Ambient temperature (K)
A= absorption coefficient
ρ= density (kg/m^3)
c_p=thermal capacity (J/kg K)



$$\frac{P}{w \cdot t \cdot v} = \text{cost} = \frac{\rho}{A} \left(c_p \Delta T + L_f + m' L_v \right)$$

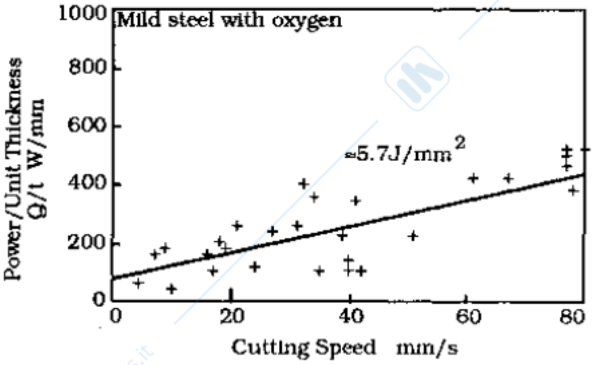
This is the cutting kerf (figure above), we cut the entire thickness t and the width w is more or less the diameter of the spot size (same order of magnitude). How much is the material

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

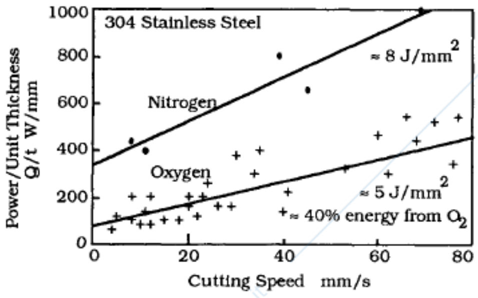
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

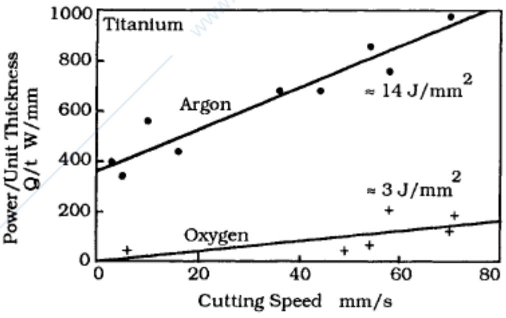
removal rate? wtv is the volume removed by unit time. If we multiply this volumetric removal rate times \rho we obtain the mass material removal rate (ρ is the density of the material). This is a melt and blow, we can estimate the amount of energy required (heat) to reach the melting temperature as $c_p(T_f - T_a)$, but we also have melting and some vaporization -->we have to take into account latent heat of fusion (L_f) + a fraction of latent heat of vaporization (L_v). We need to guess/estimate the fraction of material vaporized, we have to do it by experience. The amount of power absorbed is the incident power times the absorption coefficient (A). We can control the incident power and also w, t and v. On the contrary if the material is given, the other parameters are fixed --> we can rewrite the equation in order to obtain a constant that depends only on the material.

To check this model we can do experiments. In the figure below we can see for example that the relation between P/t and v is linear maintaining constant w and the material. Notice also that if we use a reactive gas rather than a inert gas, the power requested is lower for the same cutting speed or the cutting speed is higher for the same power. Moreover, the inert gas is more expensive → melt and blow is more expensive than reactive fusion cutting because of the lower cutting speed and the more expensive gas. But the quality obtained is better for melt and blow.



P/t for mild steel with constant *w*





$$\frac{P}{w \cdot t \cdot v} = \text{cost} = \frac{\rho}{A}\left(c_p \Delta T + L_f + m' L_v\right)$$

The difference between tha graphs of melt and blow and reactive fusion cutting is explained by the additional energy supplied by the exothermic reaction of the reactive gas. In the figure below we can see that, in general, a metal will react with oxygen forming an oxide + some energy; the amount of energy produced obviously depends on the metal which reacts with oxygen. Seeing the table we may assess that the best metal element is Chromiu, but Cr oxide immediatly cools down and coats the material, the same is for aluminum --> stainless steels and aluminum are not cut by reactive fusion cutting.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

Shielding gas: high pressure oxygen, exothermic reaction

$$x \cdot \mathrm{Me} + y \cdot \mathrm{O}_2 = \mathrm{Me}_x\mathrm{O}_{2x} + \Delta\mathrm{H}$$

ΔH [kJ mol^{-1}] is the reaction energy

Metal	Reaction	Energy ΔH [kJ/mol]
Fe	$Fe+1/2O_2=FeO+\Delta H$	260
Cr	$2Cr+3/2O_2=Cr_2O_3+\Delta H$	1150
Cu	$Cu+1/2O_2=CuO+\Delta H$	160
Ni	$Ni+1/2O_2=NiO+\Delta H$	250
Ti	$Ti+O_2=TiO_2+\Delta H$	910
Zn	$Zn+1/2O_2=ZnO+\Delta H$	350

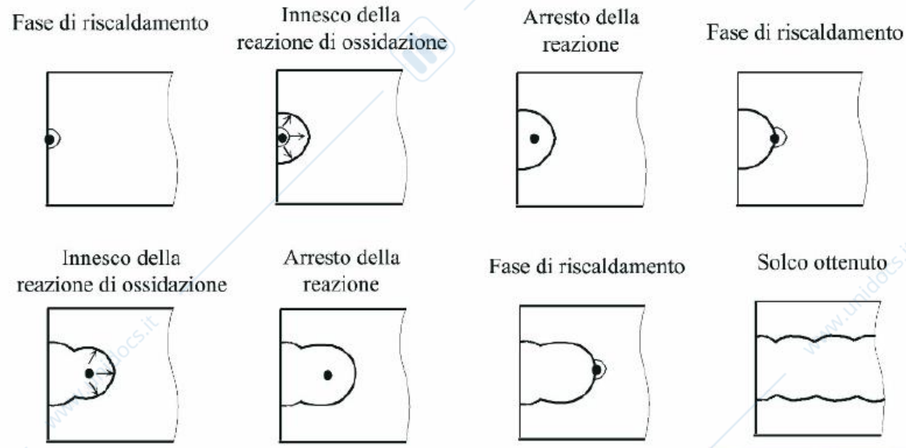
Fluid oxide dross

Frozen oxide dross
(same for Al oxides)

The edge will have some oxygen in it and will be harder and more liable to cracking

If the gas is capable of reacting exothermically with the workpiece then another heat source is added to the process.

In the figure below an explanation of striations in reactive fusion cutting.



With slow feed rate

VAPORIZATION CUTTING

We can obtain vaporization cutting when the entire material vaporizes without the need of melt and blow. It is used with metals and with nonmetals. In nonmetals we can obtain vaporization cutting also without pulsing. It is used in the cutting of materials which do not melt such as wood, carbon fiber and some plastics.

In order to take into account the fact that here the material vaporizes completely, we have to modify the previous model, let's see the figure below. The main differences with respect to before are:

- We use the entire latent heat of vaporization, and not a fraction.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

- We may assume A=1 because of the surface that vaporizes has a very high value for A.

$$A \cdot P = w \cdot t \cdot v \cdot \rho \left[c_p \left(T_v - T_a \right) + \left(L_f + L_v \right) \right];$$ with $A = 1$, *m'=1*

Thus the volume removed per unit time is **MRR=*w·t·v*** [m^3/s]

$$MRR = \frac{A \cdot P}{\rho \left(c_p \left(T_v - T_a \right) + \left(L_f + L_v \right) \right)}$$

V is the volume removed per unit time, per unit surface [m/s],

i.e. is the “penetration speed” or “rate of separation”

$$V^*S = \frac{A \cdot P}{\rho \left(c_p \left(T_v - T_a \right) + \left(L_f + L_v \right) \right)}$$

Let’s see how much is the time required to reach the vaporization point for different materials for a given power. Then, let’s see in a table how the penetration speed varies.

Assuming we have a 2kW laser focused to 0.2 mm spot diameter, the power density will be:

$$q_s'' = \frac{P_t}{S} = \frac{2000}{\pi \cdot 0.1^2} = 6.3 \cdot 10^{10}\ \text{W/m}^2$$

Since

$$T(0,t) - T_a = \frac{2 q_0''}{k} \sqrt{\frac{\alpha t}{\pi}}$$

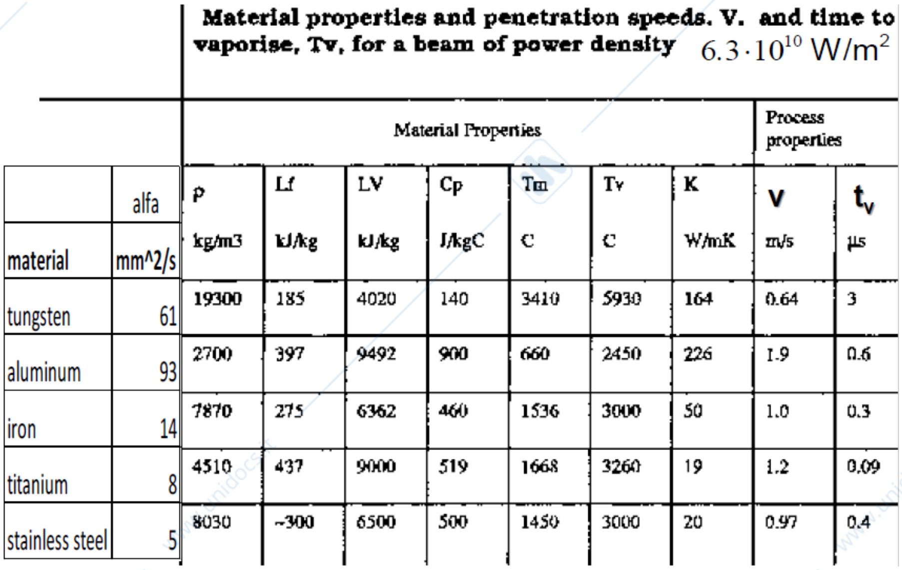
heat flow is 1D and all of it is used in the vaporisation process

$$T(x,t) = T_i + \frac{q_0'' \sqrt{4 \alpha t}}{k} ierfc \left(\frac{x}{\sqrt{4 \alpha t}} \right)$$

the boiling point T_B is reached at:

$$t_v = \frac{\pi}{\alpha} \left(\frac{k \left(T(0,t) - T_a \right)}{2 q_0''} \right)^2 = \frac{\pi}{\alpha} \left(\frac{k \left(T_B - T_a \right)}{2 q_0''} \right)^2$$

for a power density q"$_0$ $= 6.3 \times 10^{10} W / m^2$



Material properties and penetration speeds. V. and time to vaporise, Tv, for a beam of power density $6.3 \cdot 10^{10}$ W/m^2

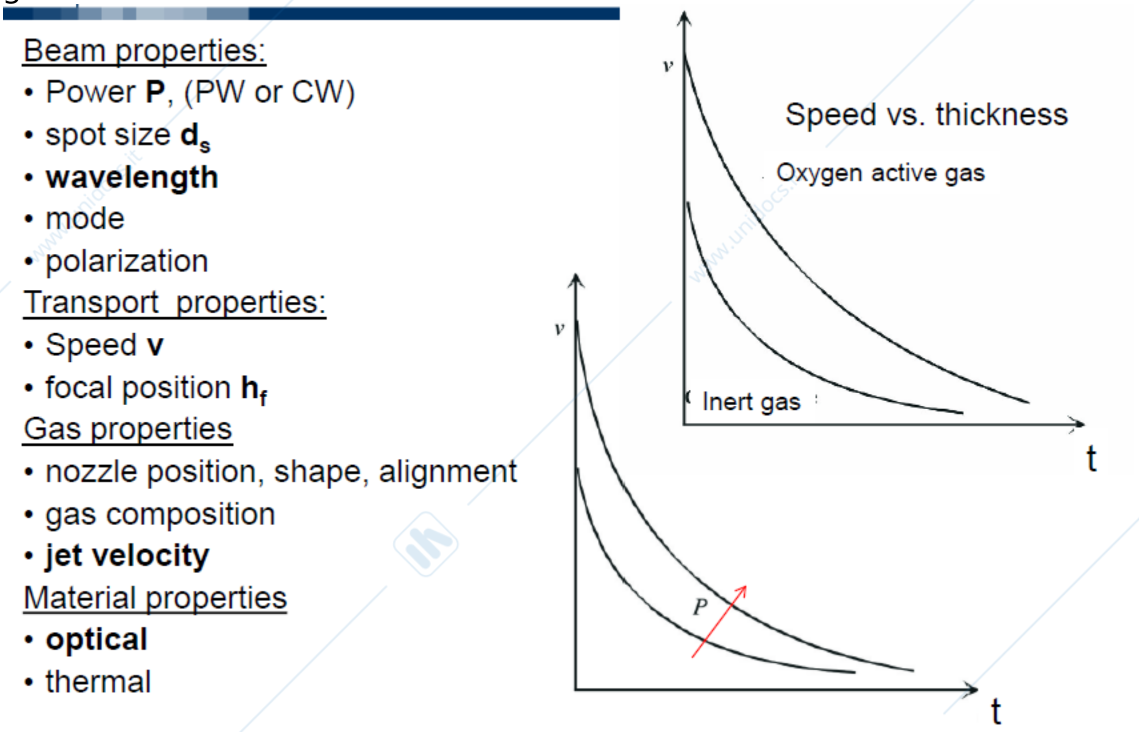
		Material Properties							Process properties	
	alfa	ρ	Lf	LV	Cp	Tm	Tv	K	**V**	**t_v**
material	mm^2/s	kg/m3	kJ/kg	kJ/kg	J/kgC	C	C	W/mK	m/s	µs
tungsten	61	19300	185	4020	140	3410	5930	164	0.64	3
aluminum	93	2700	397	9492	900	660	2450	226	1.9	0.6
iron	14	7870	275	6362	460	1536	3000	50	1.0	0.3
titanium	8	4510	437	9000	519	1668	3260	19	1.2	0.09
stainless steel	5	8030	~300	6500	500	1450	3000	20	0.97	0.4

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

LASER CUTTING PROCESS PARAMETERS

Process parameters:
1. Related to the beam: mode can be gaussian or non gaussian, polarization is not relevant for power application.
2. Transport properties
3. Gas properties: pressure of the gas in part reflects on jet velocity
4. Material properties: we should add the chemical properties with respect to the given gas.



Beam properties:
- Power **P**, (PW or CW)
- spot size **d_s**
- **wavelength**
- mode
- polarization

Transport properties:
- Speed **v**
- focal position **h_f**

Gas properties
- nozzle position, shape, alignment
- gas composition
- **jet velocity**

Material properties
- **optical**
- thermal

Notice that in general if we decrese the transverse speed, we increase the thickness of the piece we can cut. Moreover, with reactive fusion cutting we can reach higher tranverse speed for the same thickness → cheaper process. Increasing the power we can increase the tranverse speed for the same value of t. The transverse speed is the most important process parameter as in the previous technologies.

EFFECT OF SPOT SIZE

It goes around 1mm, as an assumption the cutting kerf will be equal to the spot size. The consequence of changing the spot size: if we reduce the spot size we are increasing "I" (power intensity) and we can perform different cutting mechanisms and we can go faster generally. if we decrease the spot size we also obtain better precision of the workpiece, we can cut small details. In order to have very small spot size we need very good quality (tolerances) of the torch (good alignment). If the head moves there will be some inertial effect on the torch, moreover autofocus used to maintain a constant spot size could create some imprecisions.

- 0,5 – 2 mm
- increase in power density (when decreased)
- decreased in cut thickness (when decreased)
- good alignment between nozzle and beam diameter

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

EFFECT OF WAVELENGTH

- increase in absorptivity (when decreased)
- decrease in spot dimension, for a given mode and optics train (when decreased)
- CO_2 vs Nd:YAG or Yb:Glass

Decreasing \lambda we are:

- Increasing the absorption coefficient A (see previous graphs).
- Decreasing the spot dimension for a fiven mode and optics train (we are improving the quality of the laser beam).

Moreover, remember that the wavelength of the laser depends only on the laser source, so if we want to change the wavelength we have to change the laser source.

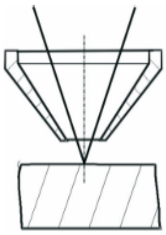
FOCAL POSITION

Focal position is strictly related to the spot size because the diameter of the spot size depends on this position; it is where we keep the workpiece with respect to the lens. Focus on the surface ($h_f = 0$) is seldom implemented, because it is very difficult to focus the beam on the surface --> you will have different situations during the work. So, companies prefer negative focus or positive focus. The best option generally is negative focus: as the material is removed the power density increases because the diameter of the beam reduces (see the figure on the notes). In reactive focus the focal position is not very important because the cutting is assisted by oxidation, but in the other processes we want negative focus.

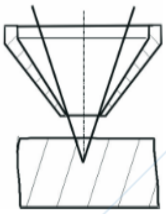
$h_f<0$: melt and blow or vaporisation cutting

$h_f=0$: reactive fusion cutting

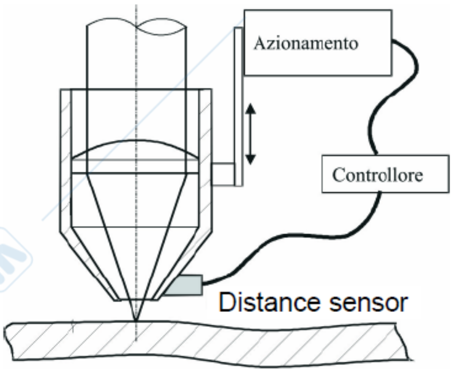
h_f has to be constant



Positive focus



Negative focus



Autofocus device

EFFECT OF GAS JET VELOCITY (PRESSURE)

Empirically we observe that if we increase the pressure at some point we have a maximum (this does not happen in water jet: in water jet if we increase the pressure maybe we have a saturation at a certain point but the cutting speed never decreases), it means that above to

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

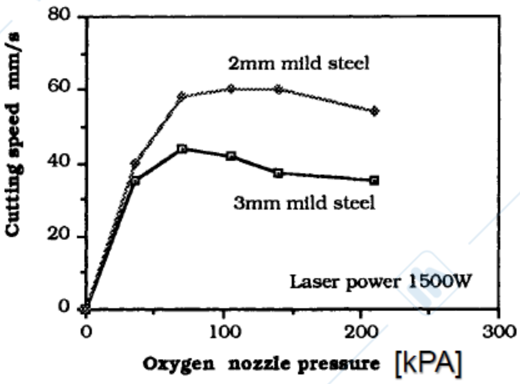
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

a certain pressure, we have to decrease the cutting speed if we increase the pressure for a given thickness. Why? Different possible reasons:

- Clogging effect: inside the nozzle there is absorption of the laser beam by the cloud of gas. In our model we haven't considered that the gas absorbs energy, we have considered the gas perfectly transparent; but with high pressure it might be some absorption of the laser.
- Turbulent flow: if we increase too much the pressure of the gas, we increase also the speed after the nozzle, so the gas may start to have turbulent flow→ it does not go straight favoring the melt and blow, it does not eject completely the material (reduced action on the cutting kerf).
- Shock waves (mechanical) inside the gas: it goes down and it bounces back and forth, so the pressure fluctuates and this reduces the blowing efficiency of the gas.

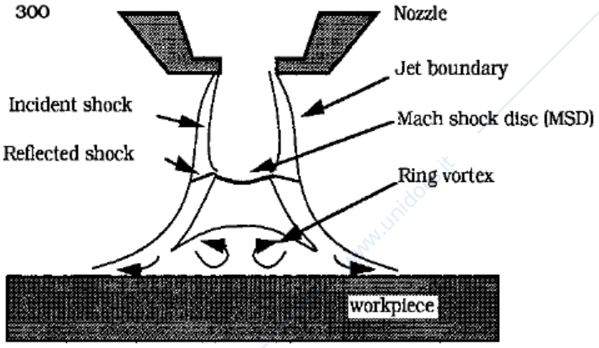
These are 3 possible reasons; we can understand that the selection of gas pressure is quite important and critical.



There seems to be a max value in cutting speed:

- clogging effect?
- Turbulent flow?
- Shock waves?

series of shock phenomena



MATERIAL PROPERTIES

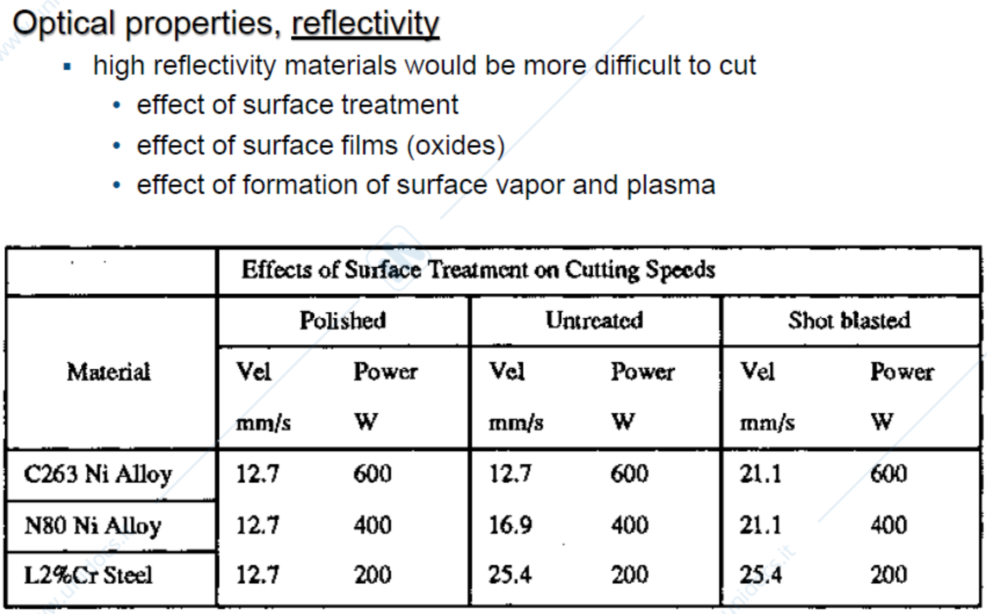
Optical properties of the materials: there are some materials that have low A or high A, the material itself determines A but also the treatment of the surface:

- Polished surface
- Untreated surface
- Shot blasted (roughed): if we treat the surface in order to increase the roughness for a given material, we can afford larger speeds, this because A is larger: this happens because the beam is reflected by the asperities and hit the material a second and maybe a third time.

Also cleaning state of the surface is important; and also the formation of film of liquid or vapor is important.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



Optical properties, reflectivity

- high reflectivity materials would be more difficult to cut
  - effect of surface treatment
  - effect of surface films (oxides)
  - effect of formation of surface vapor and plasma

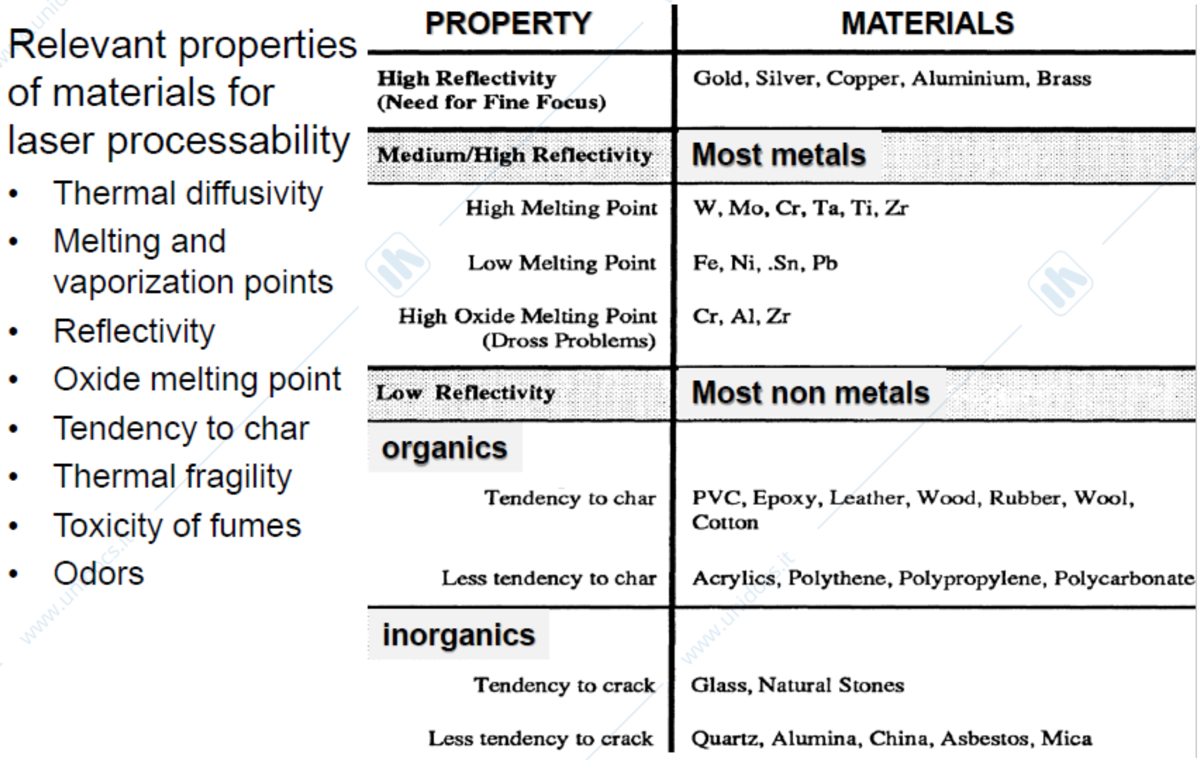
	Effects of Surface Treatment on Cutting Speeds					
Material	Polished		Untreated		Shot blasted	
	Vel mm/s	Power W	Vel mm/s	Power W	Vel mm/s	Power W
C263 Ni Alloy	12.7	600	12.7	600	21.1	600
N80 Ni Alloy	12.7	400	16.9	400	21.1	400
L2%Cr Steel	12.7	200	25.4	200	25.4	200

Let's make a comparison with water jet, what determines a higher transverse velocity in WJ?
- ductile or brittle materials (removal mechanism changes).
- for a given class of material, v will be faster for the less hard ones.
Here, in the case of laser, it's completely different. In the figure below there are all the properties concerning laserabillity (optical, thermal and chemical properties):

- Reflectivity/absorption: we can classify the material in high reflectivity and low reflectivity. High reflectivity materials are very difficult to be processed, if we want to work with them we need a very small spot size. Most metals are considered to be medium reflectivity.
- Thermal properties: if the material has a low melting point it will be worked easier. The same we can say for vaporization point. See the expression for the MRR (latent heats and c_p).
- Low reflectivity materials are good because have a high absorption coefficient, but they have tendency to char (burn) for carbon residuals. For example, if you want to cut carbon fiber you can do that but the edges will be burned, and this won't be appreciated by the customer.
- Problem with plastics: if you cut them thermally, you create fumes which are toxic.
- Inorganic materials (stones or crystals): they are transparent, we need to have very fine focus (they absorb too much); another problem is that they have a tendency to thermal cracks.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



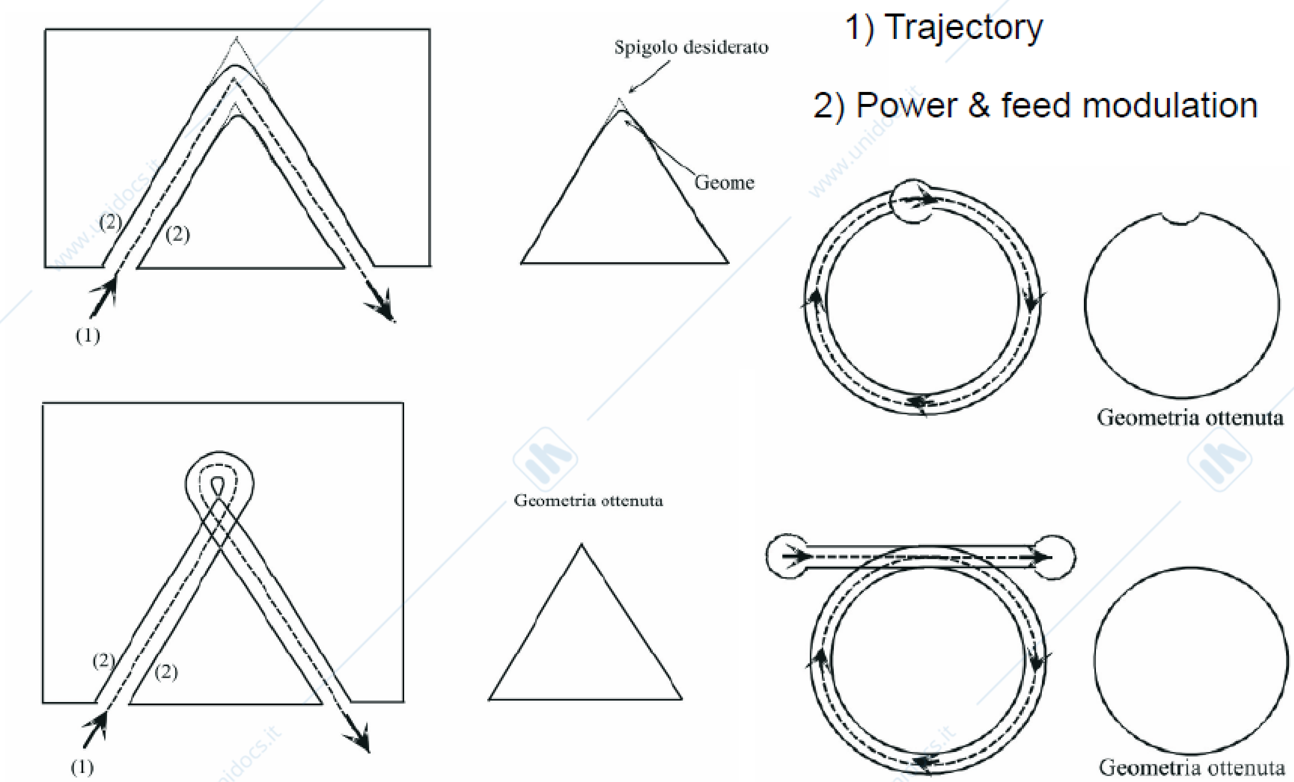
Relevant properties of materials for laser processability

- Thermal diffusivity
- Melting and vaporization points
- Reflectivity
- Oxide melting point
- Tendency to char
- Thermal fragility
- Toxicity of fumes
- Odors

PROPERTY	MATERIALS
High Reflectivity (Need for Fine Focus)	**Gold, Silver, Copper, Aluminium, Brass**
Medium/High Reflectivity	**Most metals**
High Melting Point	**W, Mo, Cr, Ta, Ti, Zr**
Low Melting Point	**Fe, Ni, .Sn, Pb**
High Oxide Melting Point (Dross Problems)	**Cr, Al, Zr**
Low Reflectivity	**Most non metals**
organics	
Tendency to char	**PVC, Epoxy, Leather, Wood, Rubber, Wool, Cotton**
Less tendency to char	**Acrylics, Polythene, Polypropylene, Polycarbonate**
inorganics	
Tendency to crack	**Glass, Natural Stones**
Less tendency to crack	**Quartz, Alumina, China, Asbestos, Mica**

CRITICAL POINTS

The feature that we use to define the quality are the same used for waterjet. There are some additional remarks:



1) Trajectory

2) Power & feed modulation

Sometimes we need to do 2D geometries, if we have a cutting kerf which is very small we

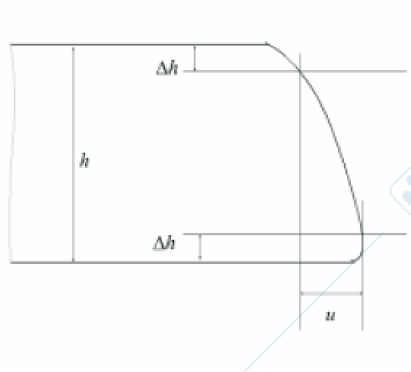
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

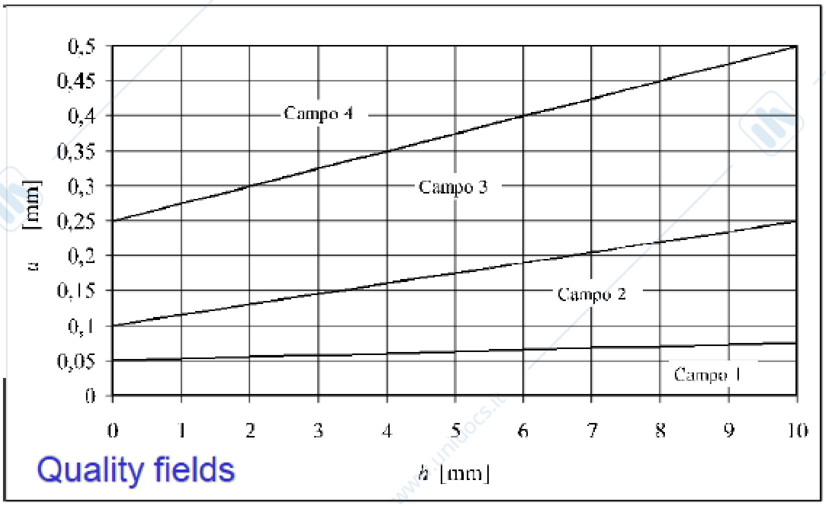
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

are able to produce fine details; but no matter how small is the spot size, if we want to make a sharp corner, we have to change direction of cutting very rapidly, but the machine necessarily slows down when it has to change direction; so the beam will stay in the angle for a longer time, so the cutting kerf in that region will be larger than expected → it is nearly impossible to obtain exactly a sharp corner. So, we can adopt some strategies in order to create some additional scrap or to deteriorate the material that is off the figure we want: we go out from the kerf, we slow down when we are out (it doesn't matter because this region is out of the figure). These tricks are used in some CAM softwares. This is possible only when we can damage the region outside of the figure.

Also in the other example (circular shape) we will start and finish outside from the perimeter we cut, in that way we can obtain a better quality of the geometry: when we start we have to stay some time in the same point because of the piercing time, while when we stop we have to slow down the machine → cutting kerf larger.

UNEVENNESS





Quality fields

Δh is proportional to the sheet thickness h:

$$\Delta h = 0.1\,h \qquad for \quad h < 2mm$$

$$\Delta h = 0.2mm \qquad for \quad h > 2mm$$

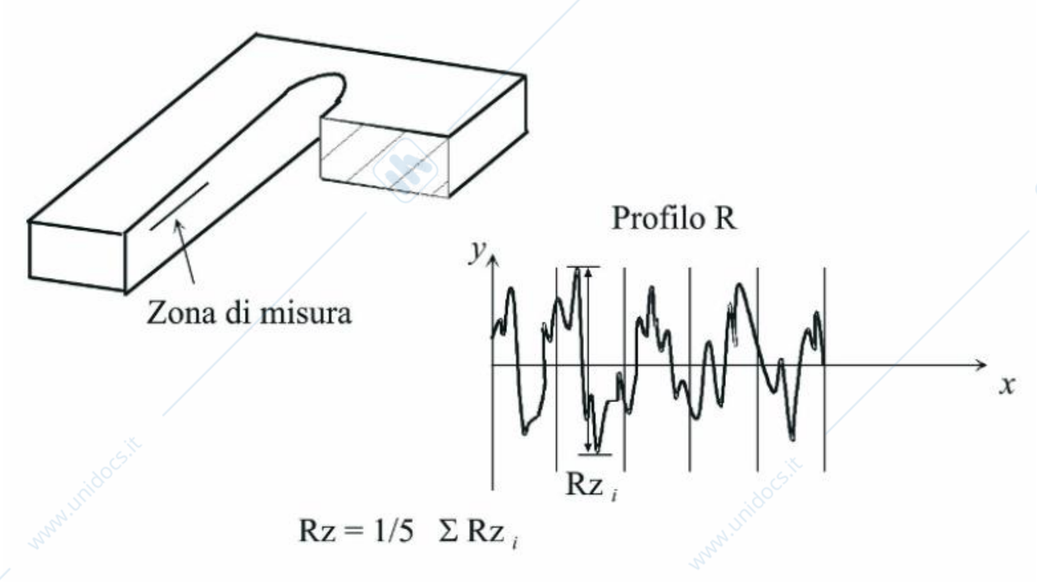
Standard DIN 2310

This is the front view of the cutting kerf, as in water-jet there is some conicity that is called unevenness. This conicity is measured through the parameter u, the points considered to measure u are not points on the top and on the bottom of the edge, but they are shifted of a certain Δh. In the graph we can say 4 different quality fields depending on the u that we can obtain for a certain thickness h. Obviously, the more little is u the better is the quality.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

ROUGHNESS



Now let's analyze the wall of the cutting kerf: generally we use a stylus meter to measure the roughness; it runs through the surface and measures the profile. The original profile is measured in a length which is defined by the standards: we have to devide the measurement into 7 segments, out of these 7 segments we put the first and the last segments out in order to remove the start and stop of the stylus. We have 3 profiles that we can take out from the rugosimeter:

- Profile P : original profile.
- Profile R : roughness, we apply a low pass filter on the wavelength, we measure the microscopic variation of the shape.
- Profile W : we measure the waviness.

Out of these 3 profiles we can measure some parameters, the 2 most important parameters are:

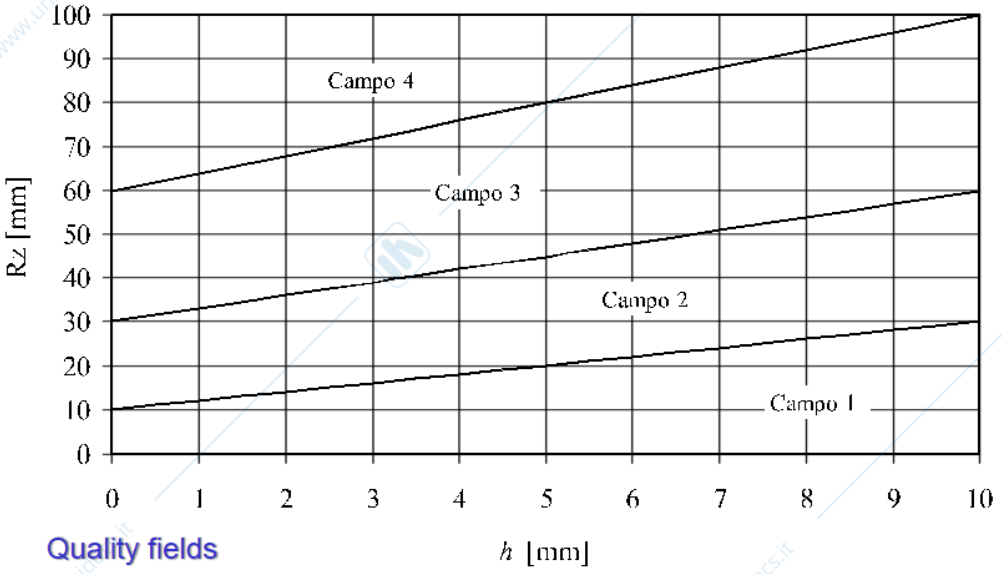
- Arithmetic mean Ra: the integral mean of the absolute value of our profile.
- Especially if we have not a regular roughness we measure Rz, it is the average of the 5 top distances between maximum and minimum height of the 5 segments.

Rz and Ra are correlated, in general Rz will be higher than Ra.

Let's see the figure below: we can have 4 quality fields also for what concerns roughness.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

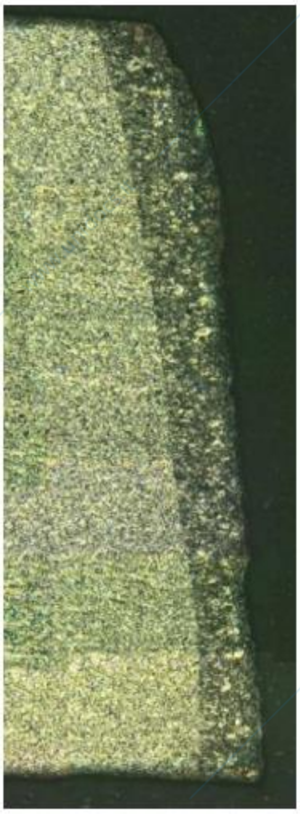
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



DROSS AND HEAT AFFECTED ZONE

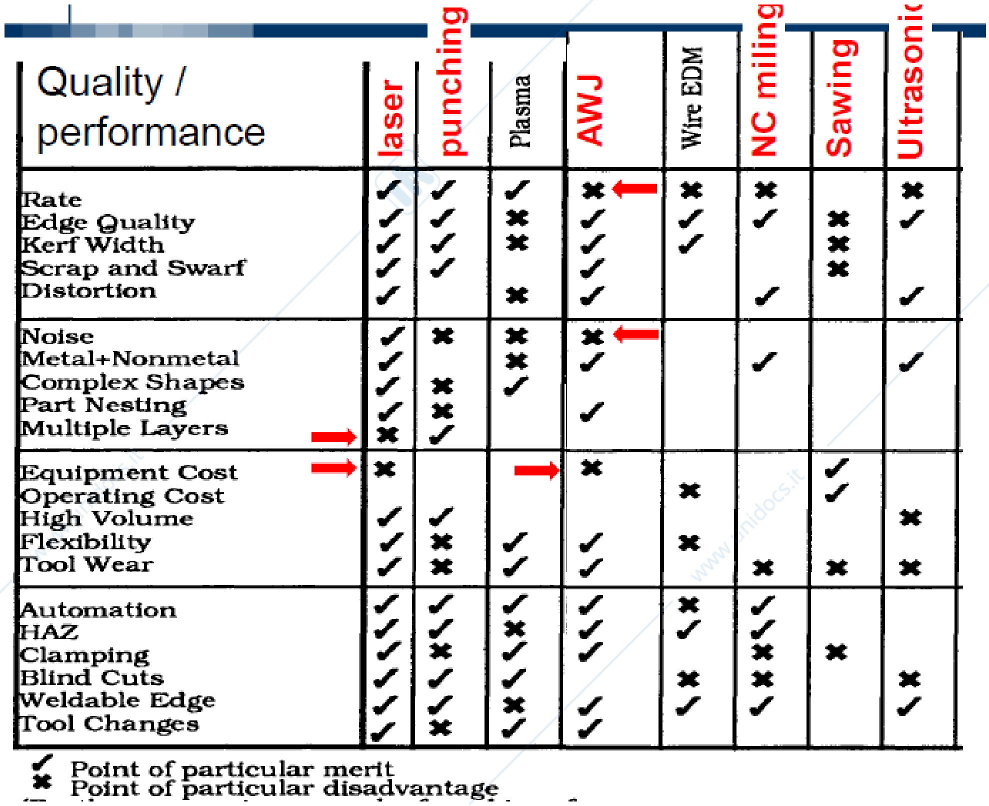
We can have other problems:

- “Bars”: remelted oxide on top edge but also on bottom edge.
- Burned edge.
- Heat affected zone.



www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

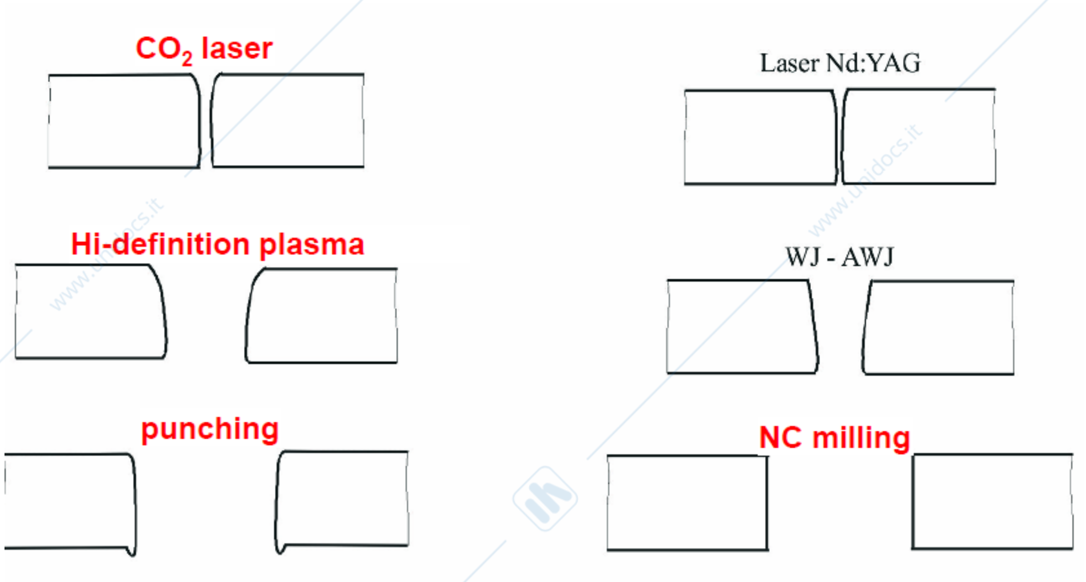
CUTTING PROCESS COMPARISONS



Quality / performance	laser	punching	Plasma	AWJ	Wire EDM	NC miling	Sawing	Ultrasoni
Rate	✓	✓	✓	✗	✗	✗		✗
Edge Quality	✓	✓	✗	✓	✓	✓	✗	✓
Kerf Width	✓	✓	✗	✓	✓		✗	
Scrap and Swarf	✓	✓		✓			✗	
Distortion	✓		✗	✓		✓		✓
Noise	✓	✗	✗	✗				
Metal+Nonmetal	✓		✗	✓		✓		✓
Complex Shapes	✓	✗	✓					
Part Nesting	✓	✗		✓				
Multiple Layers	✗	✓						
Equipment Cost	✗			✗			✓	
Operating Cost					✗		✓	
High Volume	✓	✓						✗
Flexibility	✓	✗	✓	✓	✗			
Tool Wear	✓	✗	✓	✓		✗	✗	✗
Automation	✓	✓	✓	✓	✗	✓		
HAZ	✓	✓	✗	✓	✓	✓		
Clamping	✓	✗	✓	✓		✗	✗	
Blind Cuts	✓	✓	✓		✗	✗		✗
Weldable Edge	✓	✓	✗	✓	✓	✓		✓
Tool Changes	✓	✗	✓	✓				

✓ Point of particular merit
✗ Point of particular disadvantage

PROCESS COMPARISON: KERF



LASER SOURCES AND OPTICS

GAS LASER SOURCES

First type of sources have been invented are gas sources where the active medium is a gas, typically CO2 molecule in industrial lasers. The pumping is given by an electric discharge

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

created inside the gas; gas is ionized and the electron that moves inside the resonating cavity transfer the energy to the molecules. In the table below some features of this source.

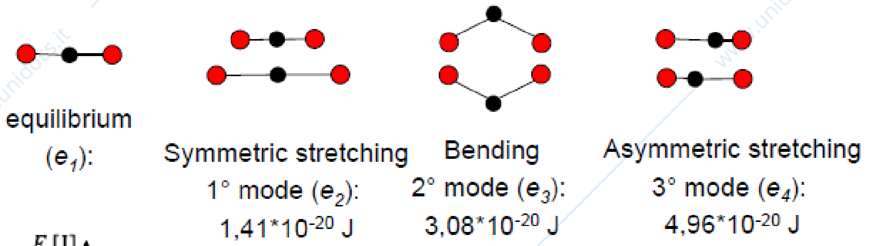
Source	**Active medium**	**Wavelength (nm)**
Gas:	molecule: CO_2	10604
	atoms: He/Ne	632.8
	ions: Kr e Ar	488 e 520

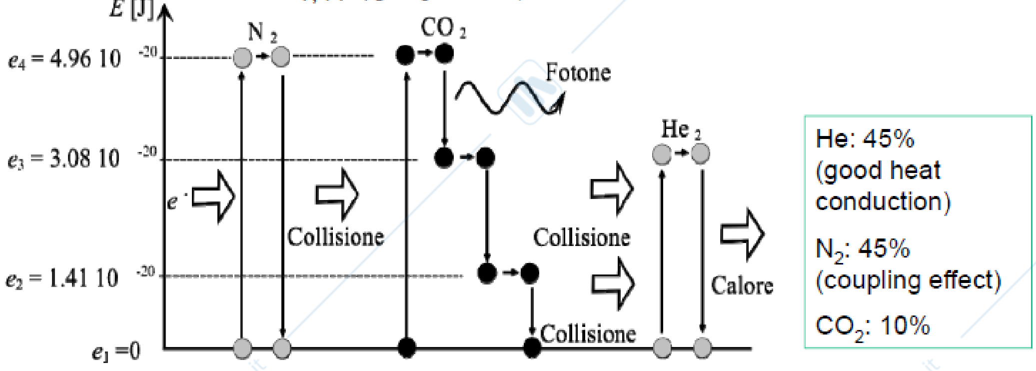
It is also called vibrational laser because we have different energetic levels for this molecule. Electric discharge is created by the voltage difference between 2 electrodes in the resonating cavity --> the CO2 jumps from the ground energetic level to the fourth energetic level. We have 4 energetic levels and each energetic level has an associated quantum energy. From the fourth energetic level there is a slow decay to the third level, this is the needed condition to have population inversion. When the molecule decays from fourth to third energetic level, we have the useful energy (photon which contributes to the energy of the laser). We give energy from e1 to e4 and we receive energy from e4 to e3, the rest is wasted. In CO2 sources we do not only have CO2 gas, it is only the 10%; we have 2 additional gases:

-nitrogen: it is much more efficient in absorbing the energy from the electrical discharge→ nitrogen is excited by electrical current and then nitrogen, by hitting CO2 molecules, gives energy to CO2.

- Helium: its purpose is to take away molecules from the third and second energetic levels → subtract energy from the lower states in order to have population inversion. Another purpose of He is to remove heat, it helps to cool down the source thanks to its good conduction properties. This cooling method is sufficient only if the power of the laser is low.

Transition energy in molecule style is between Vibration Energy Level.





Energetic numbers of the energetic levels: we can use them to compute the λ of the laser and the quantum efficiency.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

(source at low pressure)

$$\lambda \cdot f = v = c \Rightarrow \lambda = \frac{c}{f}$$

$$e_4 = e_3 + hf_{43} \Rightarrow f_{43} = \frac{e_4 - e_3}{h}$$

$$\left.\begin{matrix} \lambda = \frac{c}{f} \\ f_{43} = \frac{e_4 - e_3}{h} \end{matrix}\right\} \lambda_{CO_2} = \frac{c}{f_{43}} = 10{,}6\,\mu m$$

Near infrared

$$\boxed{\lambda_{CO_2} = \frac{c}{f_{CO_2}} = \frac{c \cdot h}{e_4 - e_3} = \frac{(3 \cdot 10^8)(6.63 \cdot 10^{-34})}{(4.96 - 3.08) \cdot 10^{-20}} = 10.6 \cdot 10^{-6}\,m}$$

$$\boxed{\eta_{qCO_2} = \frac{e_4 - e_3}{e_4 - e_1} = \frac{4.96 - 3.08}{4.96} = 38\%}$$

$$\boxed{\eta_{CO_2} \approx 10\%}$$

The value calculated for quantum efficiency is true for all CO2 sources because the quantum efficiency is inherent to the physics of CO2 laser. By playing with other parameters (pumping techniques, gas mixture, shape of the source, cooling of the source) we can try to increase the overall efficiency, but no matter how we can achieve overall efficiencies of more or less 10%, a maximum value can be 15%.

Classification

We can do classification of CO2 sources according to the gas:

- Sealed source: the gas stays inside the resonating cavity, over the time it will deteriorate because the nitrogen sooner or later will form oxides with some oxygen which will penetrate inside if the resonating cavity is not perfectly sealed; this will damage the source. In addition, with sealed source the removal of heat is more difficult. Sealed source can be a tube or a slab (lastra, placca).
- Flowing gas: here we don’t have the problem of deterioration of the gas and heat removal is facilitated because the gas is continuously changing.

We can do classification according to the direction of electromagnetic excitation with respect to the direction of laser:

- Electrodes axial with respect to the laser light.
- Electrodes transverse to the laser direction.

SEALED TUBE CO2

This is the implest design: sealed source (no flowing gas), axial electromagnetic excitation (electrodes are placed in axial direction and electrons runs axially), two mirrors at the ends of the tube, the tube is sealed.

See the characteristics in the table:

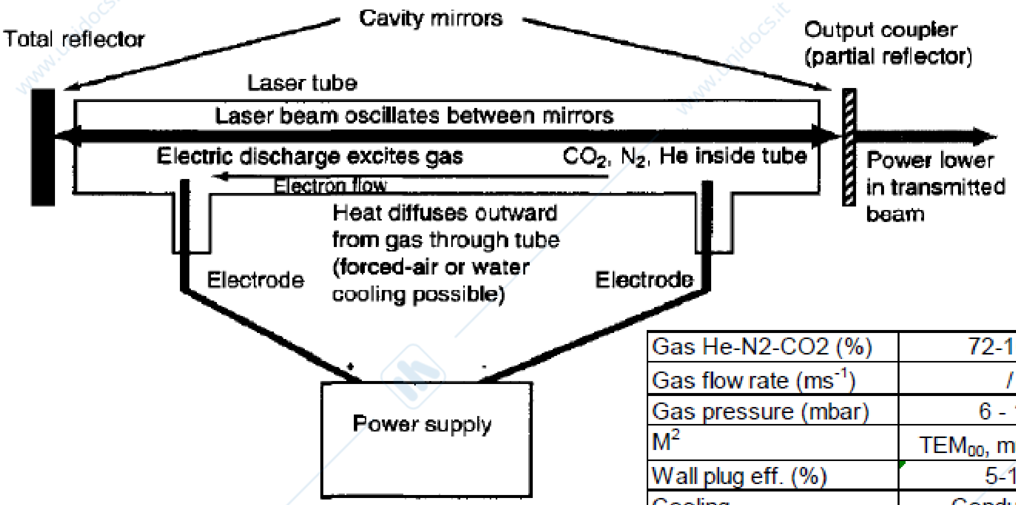
- The percentage of CO2 is only 8%, the rest is nitrogen (16%) and helium (72%).
- There is no gas flow rate because it is a sealed source.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

- The gas pressure is 6-14 mbar (lower than atmospheric pressure) because it is easier to create an electric discharge at low pressure.
- The M^2 can be the typical of a gaussian beam but also multimode.
- The overall efficiency is 5-15%.
- Cooling is only by conduction through the glass.
- It is a portable source.
- The laser can be continuous or pulsed, if we want to create a pulsed laser we must use a AC current.
- The power in output can be less than 100W which is a power suitable for marking, fusing and engraving applications (low power applications).

If you want to increase power --> slab source.



Gas He-N2-CO2 (%)	72-16-8
Gas flow rate (ms^{-1})	/
Gas pressure (mbar)	6 - 14
M^2	TEM_{00}, multimode
Wall plug eff. (%)	5-15
Cooling	Conduction
Ergonomics	Portable
Emission	PW,CW
Output power range	**<100 W**
Applications	Marking, fusing, engraving

- source coupling: low quality
- 5000 h life due to N_2 oxides

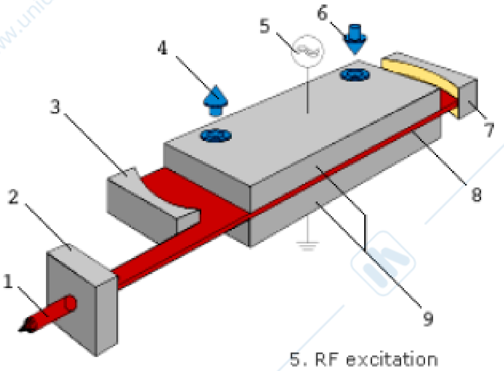
SLAB SOURCE CO2

Here we have a transverse electromagnetic excitation, the 2 electrodes are one on the top of the other orthogonal to the 2 mirrors. One of the 2 mirrors let part of the laser go through, the laser is rectangular because of it comes out from a slag. So, if we want to make it gaussian we need to have some beam shaping device outside from the resonating cavity. It is convenient because copper electrodes are directly in contact with a large surface full of gas→ they remove a lot of heat, and this is why we can increase power. In addition, electrodes can also be cooled with a circulating fluid or with forced ventilation.

In the table of typical parameters we can see that the efficiency is again good because we lose in shaping of laser but we save in cooling. The M^2 is good and the power is up to 1000W, so we can do more powerful applications than before.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

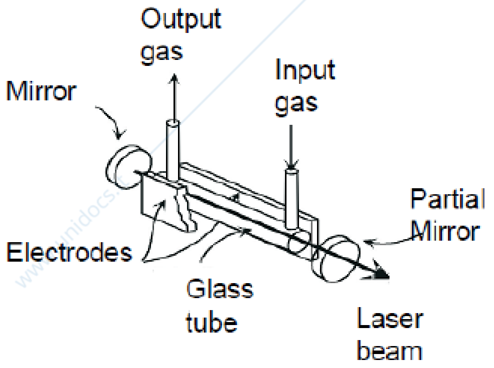


	Slab
Gas He-N2-CO2 (%)	72-16-8
Gas flow rate (ms^{-1})	/*
Gas pressure (mbar)	6-14
M^2	<1.43
Wall plug eff. (%)	5-15
Cooling	Conduction
Ergonomics	Portable
Emission	PW
Output power range	1000 W
Applications	Fine cutting, scribing, drilling, pulsed welding

- Gas is fixed in a small thermal module space
- The electrodes, made of **Cu** (RF electrodes in the figure), are sufficient to cool the gas by natural convection (no pumping systems)
- The exhaust gas must be replaced due to leakage and infiltration of O_2 (oxidation gas); duration ≈ 5,000 hours

CO2 TRANSVERSE EXCITED ATMOSPHERIC SOURCE

Again sealed source (no flow of gas), in this case electrodes are outside the tube and are transverse (current orthogonal to laser light). It is a good quality laser and it works at more or less high pressure (1000mbar). Pulsing is obtained with the frequency of the electromagnetic excitation.



Gas He-N2-CO2 (%)	72-16-8
Gas flow rate (ms^{-1})	/
Gas pressure (mbar)	**1000**
M^2	TEM_{00}, multimode
Wall plug eff. (%)	5-20
Cooling	Conduction
Ergonomics	Portable
Emission	PW
Output power range	5-20 W
Applications	Marking

- pulsed: free running
  - Spark is unstable at high gas pressure
  - Can go up to several tens of kW

FLOWING GAS CO2

If we want to increase further the power, a gas flow circulating inside the tube can be used. Here the excitation can be axial or transversal. The most important thing here is the

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

cooling method: gas is naturally cooled because it is removed from the source for some time. If the flow rate of the gas is high we can achieve a power up to 20kW.

	Slow axial flow	**Fast axial flow**
Gas He-N_2-CO_2 (%)	72-19-9	67-30-3
Gas flow rate (ms^{-1})	5-10	300
Gas pressure (mbar)	6-14	70
M^2	≈1	1-2
Wall pulg eff. (%)	5-15	5-15
Cooling	Conduction (air,w,o)	Convection
Ergonomics	Fixed	Fixed
Emission	CW,PW	CW,PW
Output power range	150-750 W	1-20 kW
Applications	Fine cutting, scribing, drilling, pulsed welding	Cutting, welding, heat treatment, drilling

Summarizing, we can increase power by:

- Improving the cooling technique: slab layout.
- Having a gas flow.

No matter you layout, the overall plug efficiency does not deteriorate with power; we increase the power without worsening the efficiency, and the same is for the quality (M^2). This is not the case for solid state sources.

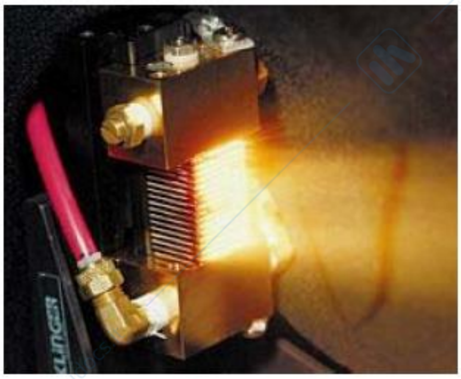
SEMI-CONDUCTOR OR DIODE LASER SOURCES

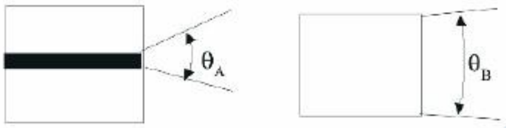
Typically they are slab sources in shape, since they are slab they are not gaussian in origin. They can be transformed into gaussian; in order to transform into gaussian beam they are generally coupled to optical fibers. Their starting shape won't have one unique divergence, but it will have 2 divergences in the 2 cross secions. If we want to increase the power we use the stack option, every interface is an individual source, so it is a modular amount of laser (the power can be increased increasing the number of stacks. It is rather compact, much smaller than gas sources with the same power. In addition, the frequency is less than 1 micron, this is very good because its \lambda is highly penetrating in many materials, this is highly appreciated. This kind of wavelength can be conductive without dissipation inside fiber glass → it can be used as a guide because glass is fully transparent to diode laser. On the contrary, for CO2 laser fiber glass can't be used as a guide because glass is not fully transparent to this kind of laser. Diode lasers are frequently used as pumping devices for Nd:YAG laser.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

Source	Active medium	Wavelength (nm)
Solid state: Semiconductor	InGaAs (diode)	810-980



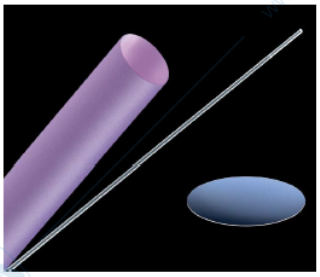


- λ = 810 nm or 970 nm (IR close to visible)
- *P* = till 6 kW with *stack* (but high divergence)
- small footprint

SOLID STATE LASER SOURCES

Solid state lasers where the second historically to be invented after CO2 lasers. The most widely diffused is the Nd:YAG laser which has a \lambda a little bit above 1 micron. We can find laser sources in form of fibers (source directly inside the fiber), rod (larger diameter and shorter length than fiber source, but both are cilindrical) and disk. But in last 10 years fiber lasers have overcome the other 2 shapes (dominant commercially).

Source	Active medium	Wavelength (nm)
Solid state: • Rod • Fiber • Disk	Nd:YAG	1064
	Yb: glass (active fiber)	1080



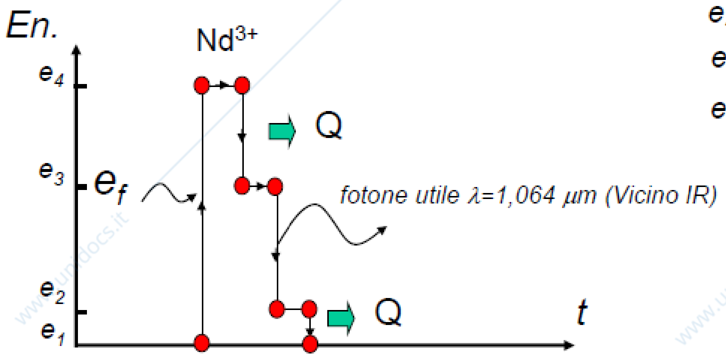
We have a rod of crystal but actually the active medium are Nd (Neodynium) ions which are implanted inside the crystal, they are the once who generate the laser light, they go in the population inversion. Again, it is a four levels quantum system. In this case pumping is optical (we provide light), ions are excited by means of external light. This external light can come from lamps or from another laser, for instance from a diode laser. Thanks to the lamp we excite Nd ions from ground energetic level (e1) to e4, then there is a fast spontaneous decay from e4 to e3 (we release energy which is lost, transformed into heat), then another transition called laser transition, it is slow from e3 to e2; in this transition we

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

emit the useful photon and as in gas source we can calculate the wavelength and the quantum efficiency knowing the energetic numbers of e3 and e2. Finally, we have another spontaneous transition from e2 to e1 with releasing of heat.

Doped Yttrium Aluminum Garnet, rod, good thermal stability
(YAG, $Y_3Al_5O_{12}$).0.1 - 1% to Nd^{3+}



e_4: 36*10^{-20} J
e_3: 22,7*10^{-20} J
e_2: 3,98*10^{-20} J

M^2 = 1 low power (100 W)
M^2 = 100 P_{max} = 4 kW

Nd:YAG lasers can be free running pulsed but also Q-switched (mechanical pulsing). Very high quantum efficiency but unfortunately the reflectors used in order to reflect lamp and to pump the source are inefficient, so the overall efficiency is very low.

$$\boxed{\lambda_{Nd:YAG} = \frac{c \cdot h}{e_3 - e_2} = \frac{(3 \cdot 10^8)(6.63 \cdot 10^{-34})}{(22.69 - 3.98) \cdot 10^{-20}} = 1.064 \cdot 10^{-6} m}$$

$$\boxed{\eta_{qNd:YAG} = \frac{e_3 - e_2}{e_4 - e_1} = \frac{22.69 - 3.98}{36} = 49\%}$$

e_4: 36*10^{-20} J
e_3: 22,7*10^{-20} J
e_2: 3,98*10^{-20} J

$\eta_{Nd:YAG} \approx 5\%$ lamp pumping
$\eta_{Nd:YAG} \approx 10\%$ diode pumping

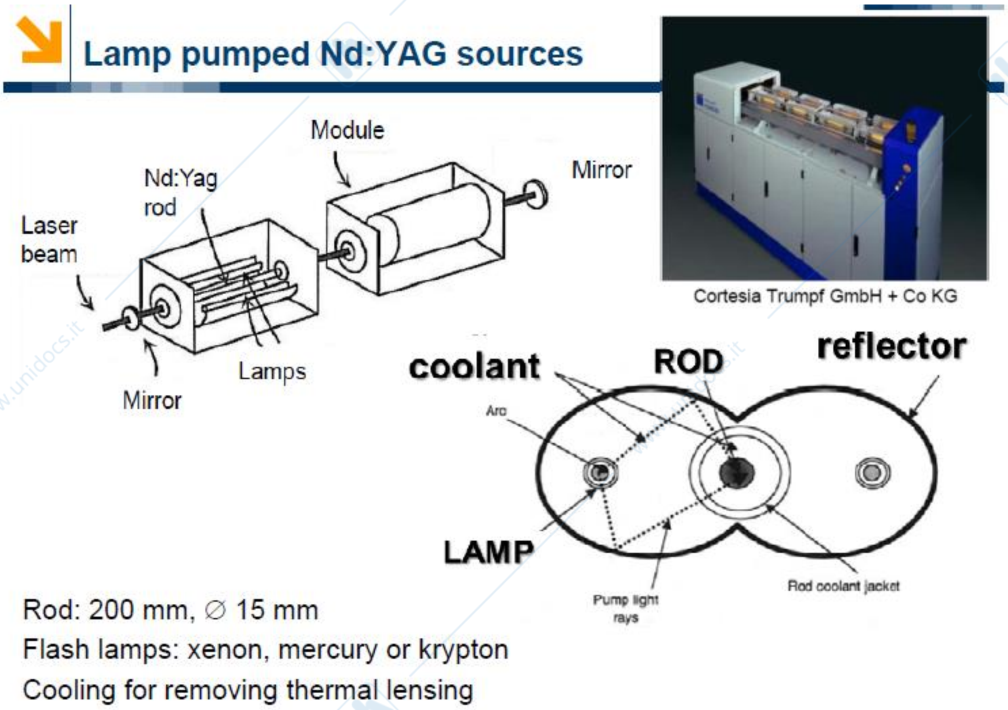
LAMP PUMPED Nd:YAG SOURCES (ROD)

Resonating cavity is axial but lamps pump light in transverse direction. The 2 reflecting mirrors are placed axially.
Remember that with diode laser you can have a modular laser because you can stack the different layers one on top of the other. Here again we can have modular laser: we can add

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

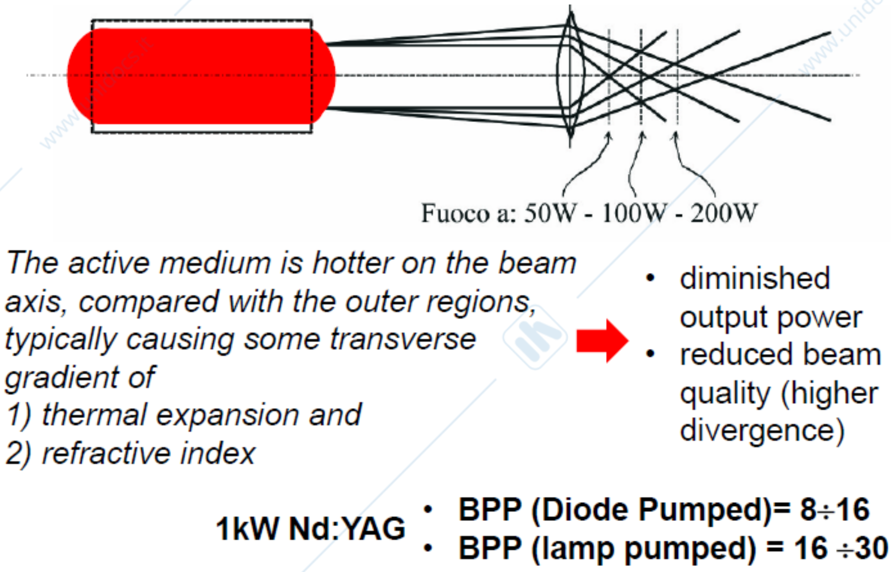
axially individual modules connecting them with the fiber. We can use the light emitted from the first laser to pump the second laser etc. Lamps are generally 2, placed on the focus of an ellipse --> the light is converged to the other focus that is the rod (laser source).



Lamp pumped Nd:YAG sources

Rod: 200 mm, ∅ 15 mm
Flash lamps: xenon, mercury or krypton
Cooling for removing thermal lensing

In solid state lasers we increase the power by increasing the power of the lamps and adding more modules. Increasing power there is a deterioration of quality and of efficiency. Why does quality deteriorates? Especially because the crystal rod heats up and gets distorted because of heating up → thermal lensing.



The active medium is hotter on the beam axis, compared with the outer regions, typically causing some transverse gradient of
1) thermal expansion and
2) refractive index

- diminished output power
- reduced beam quality (higher divergence)

1kW Nd:YAG
- **BPP (Diode Pumped)= 8÷16**
- **BPP (lamp pumped) = 16 ÷30**

Rod should be a cylinder but if we heat it up very much it will be not a cylinder anymore because its basis will not be flat. Indeed, the center of the rod is heated more than the side regions because there are more photons in the, as a consequence the right and left ends

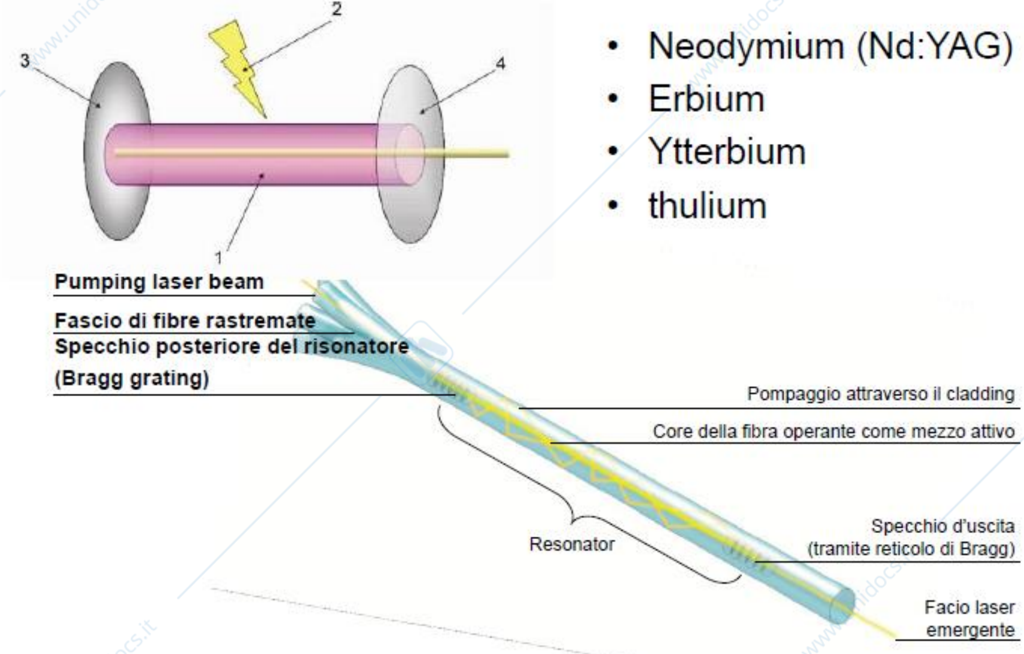
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

of the rod will not be flat anymore and they will behave as lenses; there will be a different divergence as we increase the output power --> distortion and worsening of transverse electromagnetic mode TEM. The BPP increases for lamp pumped laser, diode pumped solid state lasers are preferred because they have a better quality; this is because the heating up of the source is reduced if we pump the crystal not radially but axially.

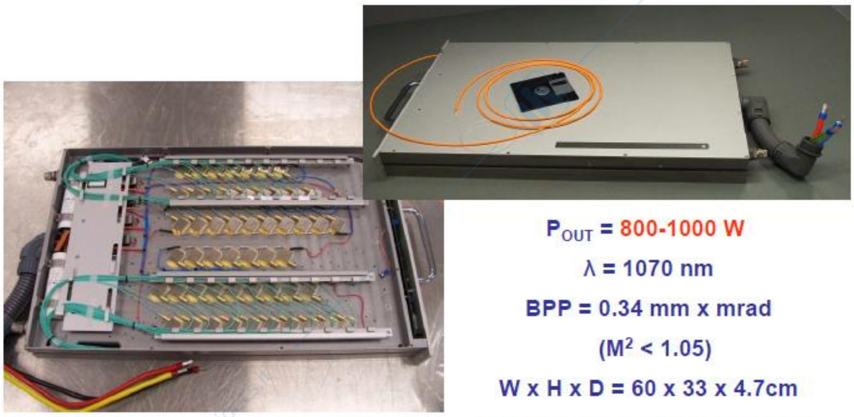
SOLID STATE LASER SOURCE (FIBER)

Solid state laser sources using fiber as active medium can be diode pumped or also they can be pumped axially to the fiber itself. The way we create a resonating cavity is with some optical devices which are engravings inside the fiber glass, their features are called Bragg gratings, they behave like mirrors (they can be fully reflective or partly reflective). We can pump the laser with a bundle of individual fibers that converge to 1 larger fiber → pumped by means of another laser. This laser is compact, efficient and also modular→ it is becoming dominant in the market.



- Neodymium (Nd:YAG)
- Erbium
- Ytterbium
- thulium

In the figure below an example of a DPSSL (diode pumped solid state laser). Notice that the quality is very good and that the overall efficiency is very high, this is highly appreciated.



P_{OUT} = 800-1000 W

λ = 1070 nm

BPP = 0.34 mm x mrad

($M^2 < 1.05$)

W x H x D = 60 x 33 x 4.7cm

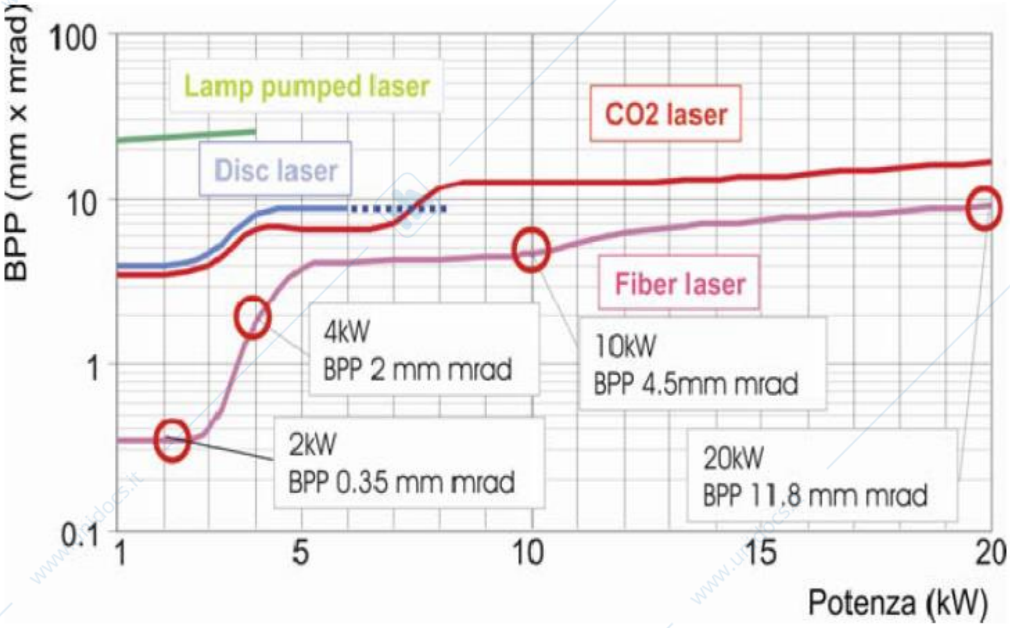
DC wall-plug efficiency > 35 %

Weight ~ 10-12kg

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

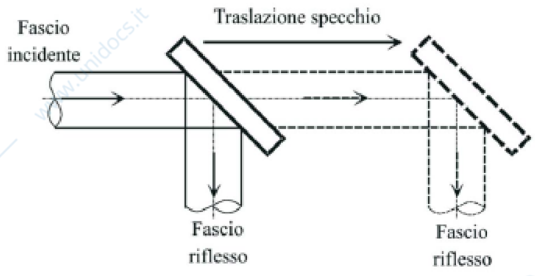
BPP VS. POWER COMPARISON

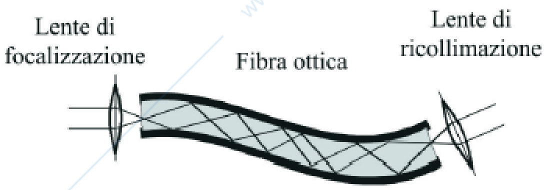


The figure above is 7 years old and this field is developing very rapidly, so probably it should be updated → now we have probably on the market lasers with higher power and lower BPP.

BEAM DELIVERY SYSTEMS

- by reflective mirrors
  - simple
  - all lasers, CW, PW
  - straight path
  - natural or forced convection, depending on power
- by transmissive fiber
  - flexible, light, no alignment problems
  - dependence on λ
  - Nd:YAG, Yb:Glass, diode
  - CW, long PW





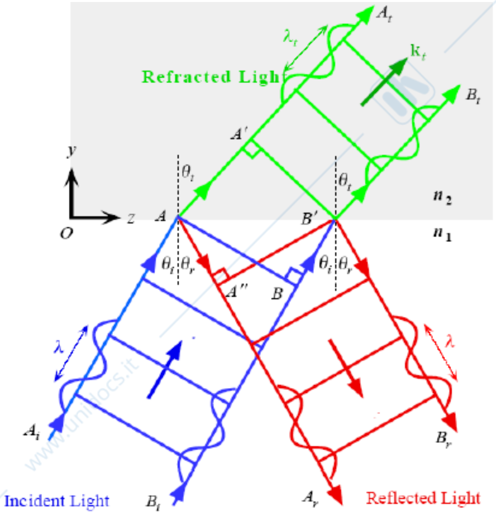
In order to transport laser we can:

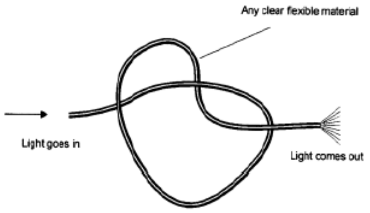
- move/rotate mirrors which can be used as delivery system for all the lasers.
- It is much more practical if we are able to insert our light into a fiber glass which is a thin wire of glass, and this can be bent to some extent. As we can see in the figure above, there will be a focusing lens which focuses the light inside the fiber and a collimation lens at the end of the fiber. The light is entrapped inside the fiber. This system can deliver only low-λ beams, otherwise the impedence of the glass is too large. If we have a fiber, it's easier to convey an axial-symmetrical TEM.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

How is possible that the light bounces inside the fiber? There are no mirror that coats the fiber inside, the fiber entraps the light naturally, the reason is the difference refraction index between 2 materials.





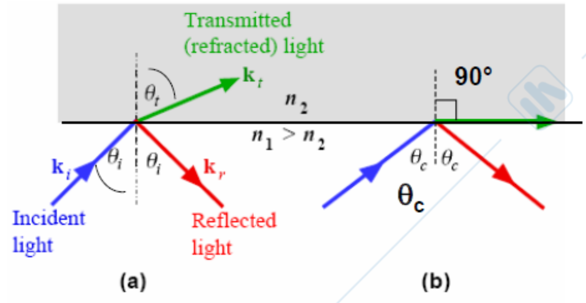
Ratio of refraction indexes
= ratio of propagation
velocities

$$\theta_i = \theta_r$$

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$ Snell law

Reflection angle is the same of incident angle while the light is transmitted with an angle that is different from the incident angle --> part of the energy will be transmitted and part of the energy will be reflected when a beam of light tries to escape out. Transmitted wavelength changes a little bit (this is the refraction phenomenon), while reflected wavelength does not change.

Let's suppose that we have glass and air as the 2 media: we can define the refraction index of the 2 media:
By definition, the refraction index is the ration between the speeds of the light inside the 2 media; in general light travels faster in air and slower inside the solid medium. Snell law is used to calculate the refracted angle theta_t. We want theta_t to be at least 90° --> beam transmitted parallel to the fiber itself in the worst case. There will be a cone of acceptance--> if the beam is inside the cone of acceptance it will remain inside the fiber, otherwise it will escape. If a ray will be more orthogonal with respect to the cone of acceptance, it will escape, we can define a critical incident angle, if the incident angle is higher than the critical angle, the light will be maintained inside the fiber glass.



Total internal reflection

glass $n_1 = 1.5$
air $n_2 = 1$

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{\sin\theta_i}{\sin\frac{\pi}{2}} = \frac{n_2}{n_1} \rightarrow \sin\theta_c = \frac{n_2}{n_1}$$

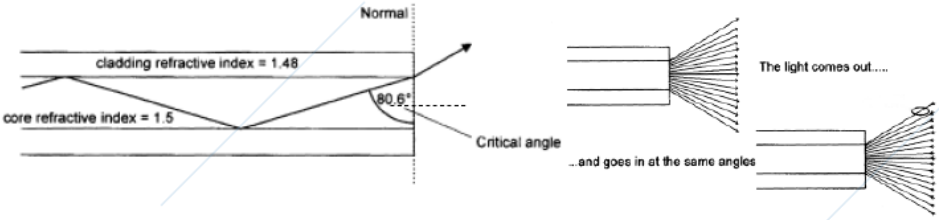
$$v_1 = \frac{n_2}{n_1} v_2 \approx 2 \cdot 10^8 \text{ m/s}$$

$$\sin\theta_c = \frac{1}{1.5} \rightarrow \theta_c = 46°$$

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

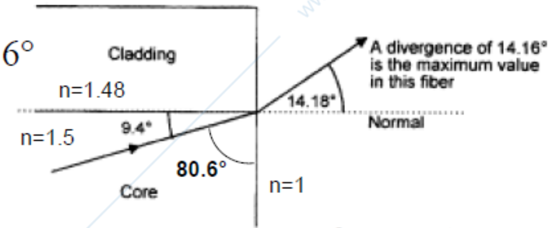
Any ray with an incident angle lower than 46° will escape in the example above. Glass exposed to air would be good, but it is impossible to use pure glass at interface with air because it will dirt very rapidly with dust and if there is dust on the boundary of the 2 media, this dust will act as an escape point for light, it will dissipate power light. The only option is to use 2 different glasses with 2 different refraction indexes trying to achieve a good critical angle (figure below). Remember that the refraction index of air is taken equal to 1 as reference to calculate the others refraction indexes.



$n_1 = n_{core} = 1.5$

$n_2 = n_{cladd} = 1.48$

$$\theta_c = \arcsin\frac{1.48}{1.5} = 80.6°$$

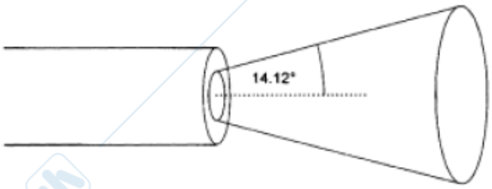


cone of acceptance

Unfortunately the critical angle is high because n1 and n2 are similar →Only the rays in the range of 9.4° will remain inside the fiber.

Moreover, we have to consider even the situation at the inlet and at the outlet of the fiber glass: when the ray moves from core material to air or viceversa, it is refracted of a certain angle. We can determine the cone of acceptance; for example at the inlet we want that, as a consequence of refraction from air to core, the rays will have an incident angle higher than the critical angle → the angle which allows to match this situation determines the cone of acceptance, and this cone is the same at inlet and outlet of the fiber (see the exercise done with the tutor).

numerical aperture and the cone of acceptance are both measurements of the light gathering capability



$$NA = \sqrt{n_{core}^2 - n_{cladd}^2}$$

$$NA = \sqrt{1.5^2 - 1.48^2} = 0.244$$

$$acc.angle \cong \arcsin(NA)$$

$$acc.angle \cong \arcsin(0.244) = 14.3°$$

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

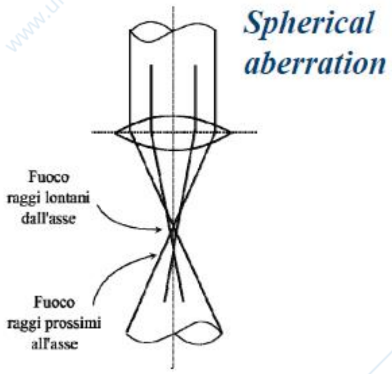
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

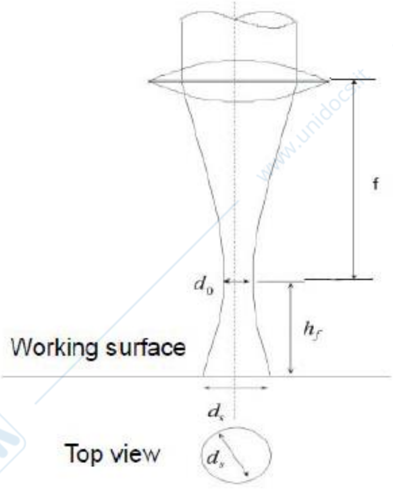
It can be demonstrated (see exercises) that the acceptance angle, though which we can determine the cone off acceptance, can be calculated as the arcsin of the numerical aperture (NA), which is property of the fiber glass (it depends on the refraction indexes of core and cladding). Notice that if the 2 indexes are very different, the angle of acceptance is higher and thus the situation is better (we can allow higher slope of the laser at the inlet of the fiberglass).

OPTICAL TERMINOLOGY

Now let's analyse the situation at the workpiece. We can assume to have a cylindrical ray at the beginning and we want to focus it as much as possible in order to increase the power density of the beam (it depends on the application we want to obtain). In order to focus the ray we can use a focusing lens. The focusing lens is characterised by a certain focal length (f) which is the distance between the lens and the point where the minimum diameter of the beam is reached (d_0), this is called waist diameter. Notice that if we imagine the laser beam composed of many rays, we can easily say that the rays at difference distances from the center of the beam are focused at different focal distances → the shape of the beam after the lens is a hyperboloid where the minimum diameter is not zero but is d_0. In addition, the workpiece may be at a certain distance from the point where the diameter of the beam is the minimum one → the focal height is that distance (h_f). Notice that if h_f is not zero, the spot size that we obtain on the workpiece has a diameter d_s which is higher tham d_0; d_s is the spot diameter.

- focal length ***f*** *(not frequency!)*
- waist diameter $\boldsymbol{d_0}$
- focal height $\boldsymbol{h_f}$
- spot diameter $\mathbf{d_s}$





Moreover the focal length is only a theoretical parameter that can only be used if the incident beam (beam before the lens) is perfectly cylindrical; but the beam usually is not perfectly cylindrical but it is a little bit divergent → the actual focal length (z_0) is different from the ideal/theoretical focal length (f) (see the figure below).

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

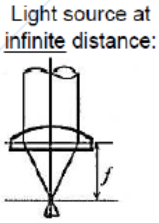
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

- actual focal position z_0
  - Depends on incident beam

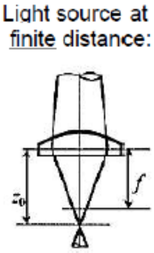
- Ideal focal length f

$$z_0 \approx f$$

- 2.5”, 5”,7”
- 63, 127, 150 mm



Cylindrical incident beam



Conical incident beam

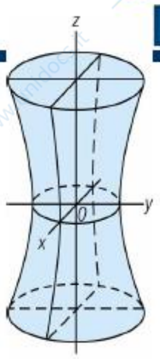
Now let’s see the figure below: if the incident angle is divergent it means that the diameter of the beam at the outlet of the laser source (or of the fiber glass/mirrors) (d_f) is lower than the incident diameter of the beam (d_l). Assuming that the left part of the cross section of the hyperboloid is a triangle, we can calculate easily that the angle of convergence of the beam is θ (figure below). If we neglect the divergence of the beam before the lens we can say that θ is about equal to $\frac{d_f}{f}$. Using the usual equation that is valid in every point of the beam, we can calculate the value for d_0 → we can compute the maximum power density that we can obtain.

Waist (minimum) diameter

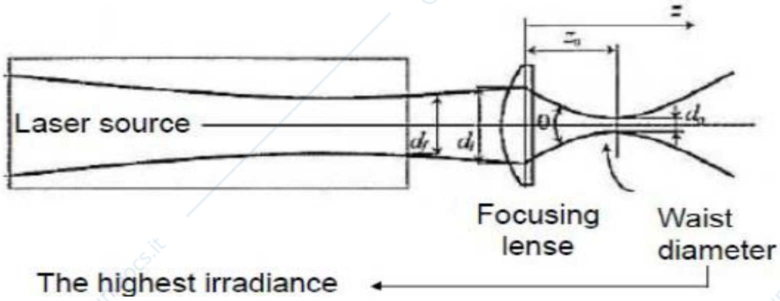
35

$$\theta = 2arctg\left(\frac{d_l}{2}\cdot\frac{1}{z_0}\right) \cong \frac{d_f}{f} \qquad \text{ma} \qquad d_0\theta = k\lambda$$

$$d_0 = k\frac{\lambda}{\theta} = k\frac{\lambda\cdot f}{d_f} = k_G\cdot M^2\frac{\lambda\cdot f}{d_f} = \frac{4\cdot M^2}{\pi}\frac{\lambda\cdot f}{d_f}$$



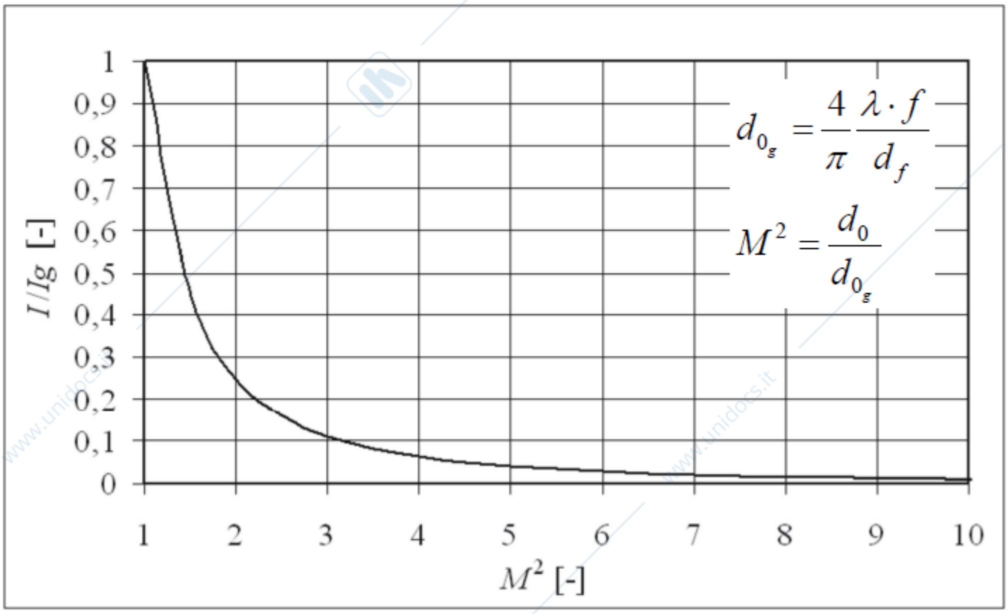
caustic or hyperboloid



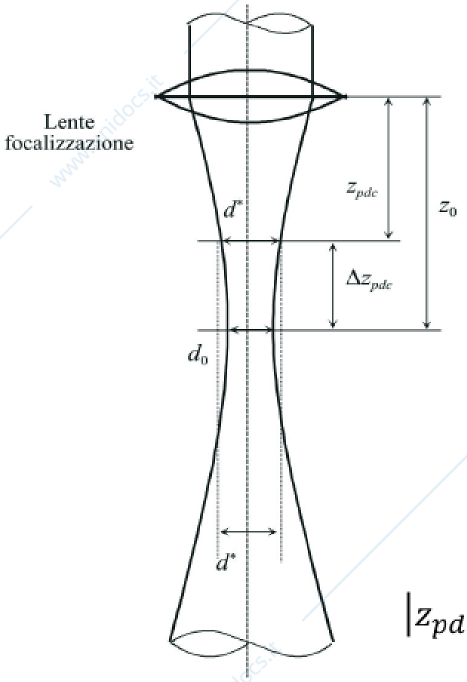
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

In the graph below we can see that if the beam is Gaussian we can reach the minimum waist diameter and so the maximum power density obtainable with a certain power (M^2 is the minimum possible so the waist diameter is the minimum possible).



Now let's introduce the "depth of field" or "depth of focus": when the laser is working on a workpiece, we have previously said that it's difficult that the distance between lens and workpiece is equal to the focal distance. In other words, is difficult that the diameter of the spot (d_s) is equal to the waist diameter (d_0). Thus, we have to determine which is the highest variability from d_0 which we can accept. In general we can accept a certain d_s which is higher than d_0, we can call d* the critical value for d_s.



$$d^* = h \cdot d_0 \quad \text{con} \quad h > 1$$

With h
arbitrarly assigned,
e.g. 1.41

Si può dimostrare che:

$$d^2(z) = d_0^2 + (z - z_0)^2 \theta^2 \Rightarrow$$

$$|z_{pdc} - z_0| = \frac{\sqrt{d^{*2} - d_0^2}}{\theta} \Rightarrow$$

$$|z_{pdc} - z_0| = \Delta z_{pdc} = \frac{\sqrt{h^2 d_0^2 - d_0^2}}{\theta} = \sqrt{h^2 - 1}\,\frac{d_0}{\theta}$$

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

Knowinf the (hyperboloid) shape of the beam we can calculate the depth of field: the maximum variability from the focal position which allows us to have a spot diameter lower than the critical spot diameter (d_s<d*) → we have a power intensity which remains enough high for the process we want to do. Therefore, in general the depth of field depends on the minimum power density which allows us to do the process.

$$\Delta z_{pdc} = \sqrt{h^2 - 1}\,\frac{d_0}{\theta}$$

$$\begin{tikzcd} & \Delta z_{pdc} = \sqrt{h^2 - 1}\,\frac{d_0^{\,2}}{k \cdot \lambda} \\ \boxed{\begin{array}{l} \theta = \frac{k\lambda}{d_0} \\ \theta \cong \frac{d_f}{f} \end{array}} \arrow[ur] \arrow[dr] & \\ & \Delta z_{pdc} = \sqrt{h^2 - 1}\,\frac{d_0 \cdot f}{d_f} \end{tikzcd}$$

As we can see in the figure above, we can write the depth of field in different ways. Moreover notice that the smaller is the waist diameter, the higher is the maximum power density (given a power) but the lower is the depth of field. Therefore, when we have fine focus (small diameter), we also need to enforce a very good precision in position control of both the lens and the workpiece (high-quality autofocus) because the depth of field is short.

Now, we can conventionally define the depth of field assuming $h = \sqrt{2}$. With this assumption (figure below): the Gaussian will have the smallest depth of field → other TEM could be preferable in case we need a larger depth of field (exercise with tutor→ the depth of field of Gaussian beam increases in absolute value but not in realative value: the variation of diameter along the beam is higher for gaussian beam).

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

$$\Delta z_{pdc} = \left|z_{pdc} - z_0\right| = \sqrt{h^2 - 1}\,\frac{d_0 \cdot f}{d_f}$$

$$M^2 = \frac{d_0}{d_{0_g}}$$

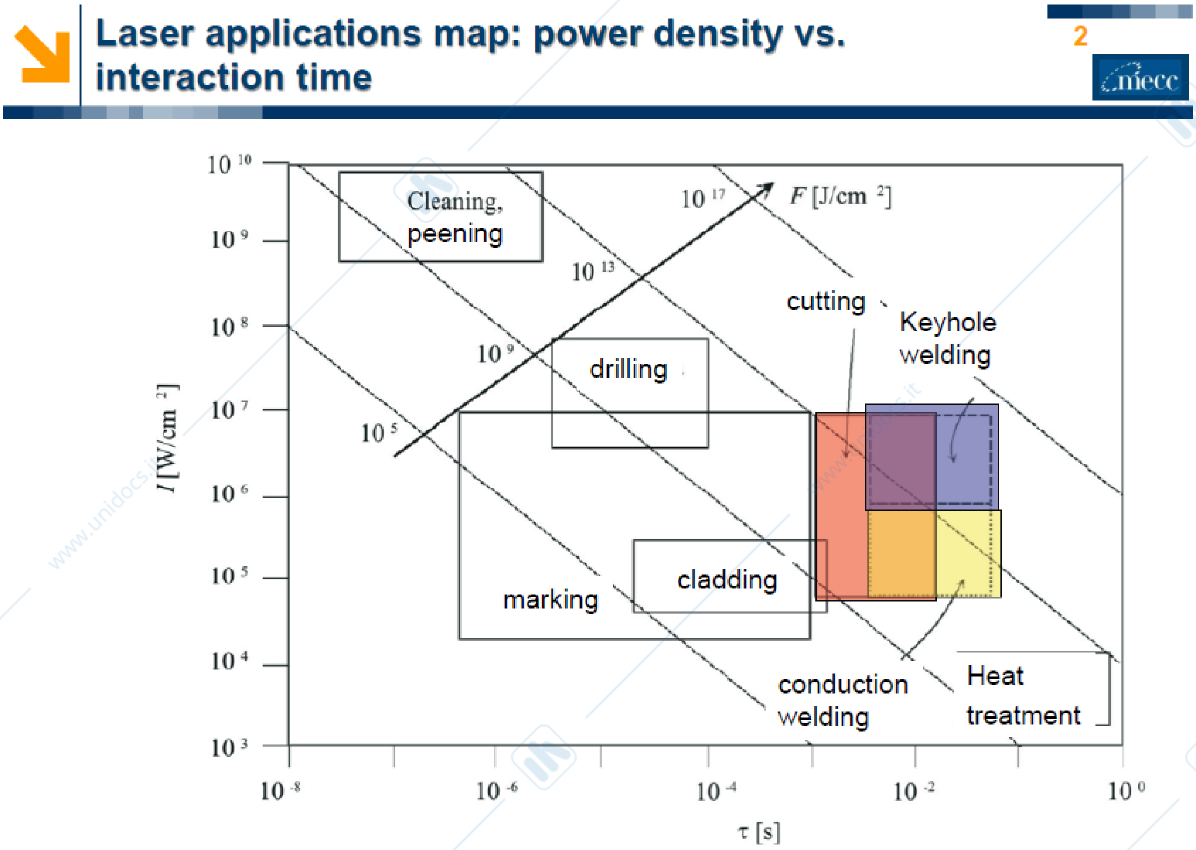
$$\Delta z_{pdc} = \left|z_{pdc} - z_0\right| = \sqrt{h^2 - 1}\,\frac{d_{0g} \cdot f}{d_f} M^2 = \Delta z_{pdc_g} M^2$$

considering: $h = \sqrt{2} = 1{,}41$

Gaussian beam with: $\Delta z_{pdc_g} = \frac{d_{0g} \cdot f}{d_f}$

Non Gaussian beam: $\Delta z_{pdc} = \frac{d_{0g} \cdot f}{d_f} M^2$

WELDING AND OTHER APPLICATIONS



Laser applications map: power density vs. interaction time

2

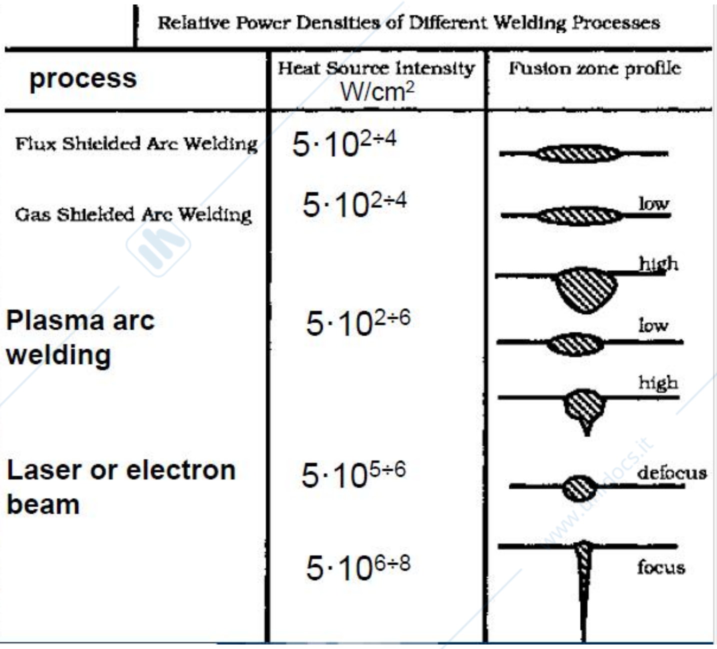
How do we change the application? Mostly by varying the interaction time and the power density. If we have small interaction time and high power density, we can perform for instance drilling (foratura); if we have longer interaction time, we can do cutting and also welding; going a little bit slower with the travel speed we can obtain welding (we increase the interaction time); we have 2 distinct welding processes which are “keyhole welding” and “conduction welding”; we can switch from one mechanism to another one simply by

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

increasing the power density → for a given material, for example steels, if we exceed a threshold power density (10^6 in the graph), we can move from conduction to keyhole welding. We can increase the power density by reducing the diameter, by increasing A, by place in a better way the workpiece, by increasing the wavelength etc. The power density is the most important process variable that determines what weld process we have and what kind of weld seam/shape we can obtain (figure below).

If we have a defocused or low power density laser beam, we will have a conduction limited welding pool, so the welding seam will look like a pool with isothermal curves which are more or less semi-circular. On the contrary if we have a focused beam or high power density beam (I above 10^6), we instantaneously produce plasma that changes the A, and also changes the way the energy is conducted inside the material → The welding seam will be much more vertical than horizontal. In the figure (last cross section of welding seam) we can see a keyhole welding --> plasma column forms inside the material, no isothermal lines of conduction (which are semi-circular), so no heat conduction takes place during this welding process --> plasma column has a vertical propagation.



Relative Power Densities of Different Welding Processes

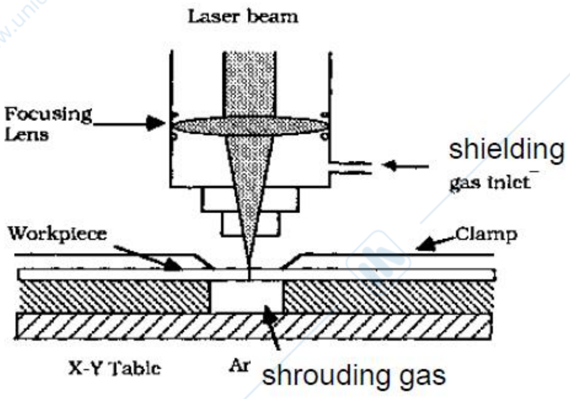
process	Heat Source Intensity W/cm²	Fusion zone profile
Flux Shielded Arc Welding	$5\cdot10^{2\div4}$	
Gas Shielded Arc Welding	$5\cdot10^{2\div4}$	low high
Plasma arc welding	$5\cdot10^{2\div6}$	low high
Laser or electron beam	$5\cdot10^{5\div6}$	defocus
	$5\cdot10^{6\div8}$	focus

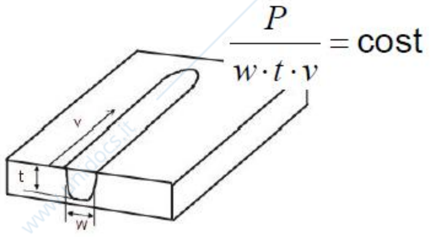
We obtain plasma column also in cutting, but in cutting we have a gas which ejects the dross out of the cutting kerf. Also in welding there is a gas, but the pressure of this gas is not studied to eject the dross out of the welding zone. If we use laser welding but with a low power density, the shape of the welding seam which takes place is comparable to the ones of other welding processes, but we have a higher cost and the performances are similar → it doesn't make much sense to use laser welding with low power densities. While the shape of the keyhole welding seam is completely different from the ones of all the other technologies. In reality this kind of welding seam can also be obtained with electron beams but these beams require to be operated in vacuum environment, so they are much more expensive and for this reason are used only for micro operations on small components.

GENERAL EQUIPMENT SETUP

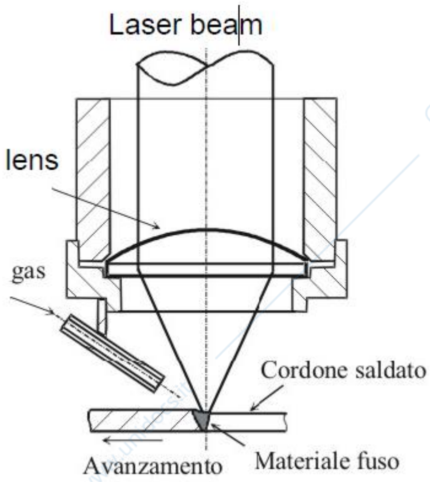
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari





$$\frac{P}{w \cdot t \cdot v} = \text{cost}$$

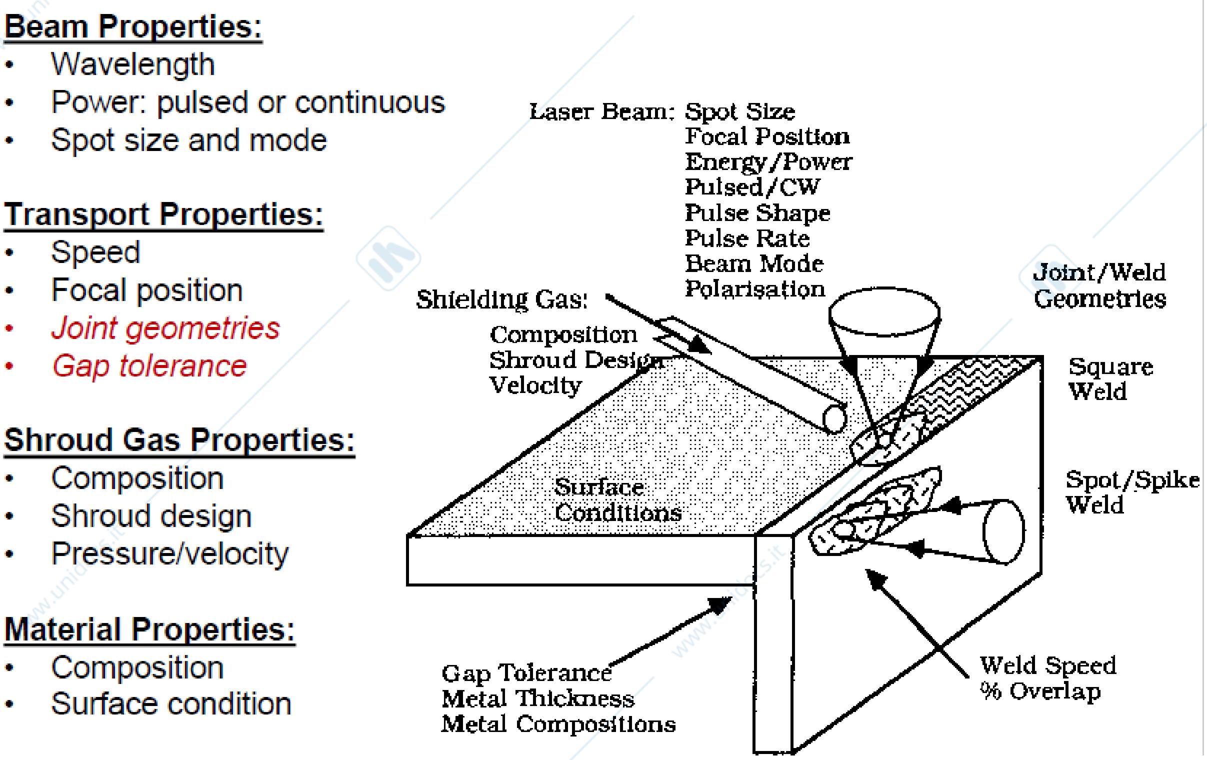


We need welding head, focusing length that we can adjust in vertical position in order to focus, gas assist required to protect the lens and not to blow the material away from the gap but to blow away the vapor of plasma that forms above the sheet. Indeed, plasma comes from the metal but also from the gas itself-->the plasma cloud would block the laser light. So, most likely we don't only need a shielding gas inside the welding head, but we need also lateral or surrounding gas (shrouding gas) which blows away the cloud of plasma and protects the welding seam from oxygen (oxidation will prevent welding to take place). Both the 2 gases can only be inert gases (argon helium CO2). The equation for material welding rate is very similar to the equation used for cutting, also the layout is similar, the 2 main differences are:

- treatment of gas (lower pressure) and we need a shrouding action.
- if you want to obtain keyhole welding especially on thin sheets you need very good clamping and positioning of the sheet, it is one of the biggest limitation in laser welding, because we want to be fast and not to waste time in proper positioning--> It is one of the main reason why laser welding is not so much diffused as it would be if there wasn't this problem.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari



Beam Properties:
- Wavelength
- Power: pulsed or continuous
- Spot size and mode

Transport Properties:
- Speed
- Focal position
- *Joint geometries*
- *Gap tolerance*

Shroud Gas Properties:
- Composition
- Shroud design
- Pressure/velocity

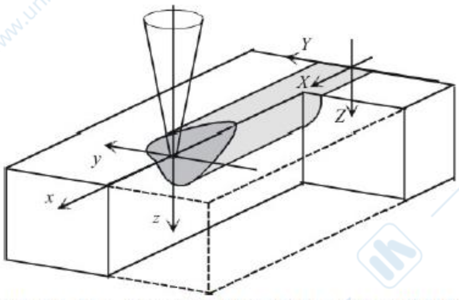
Material Properties:
- Composition
- Surface condition

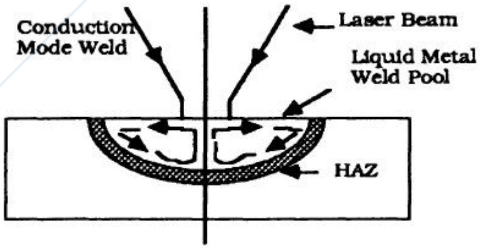
CONDUCTION LIMITED WELDING

Conduction limited welding: shape of the welding pool is typical of heat conduction inside the material (semi-circular shape of isothermal lines). The shape ratio (aspect ratio) will depend on the welding speed (figure below), v high → weld pool shallower. The material on the top is liquid with different temperatures inside during the welding process --> no homogeneous. You will have some steer recirculation of the liquid due to the high thermal gradient, this steering effect will be reflected somehow in the metallurgical properties of the welding seam. The shape of the welding pool is shorter in the direction of travel of the pool and is longer in backward direction.

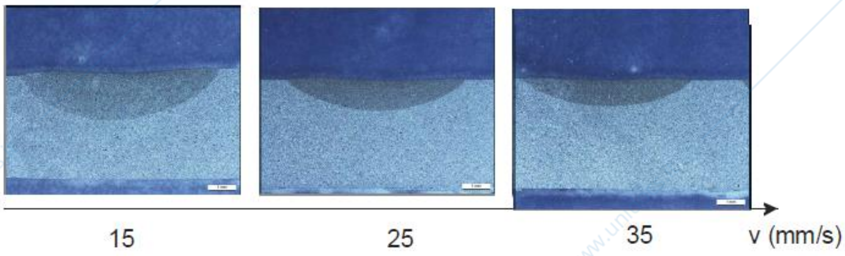
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

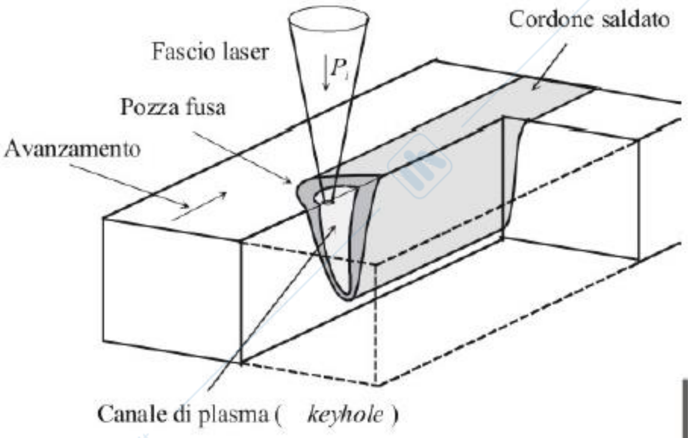


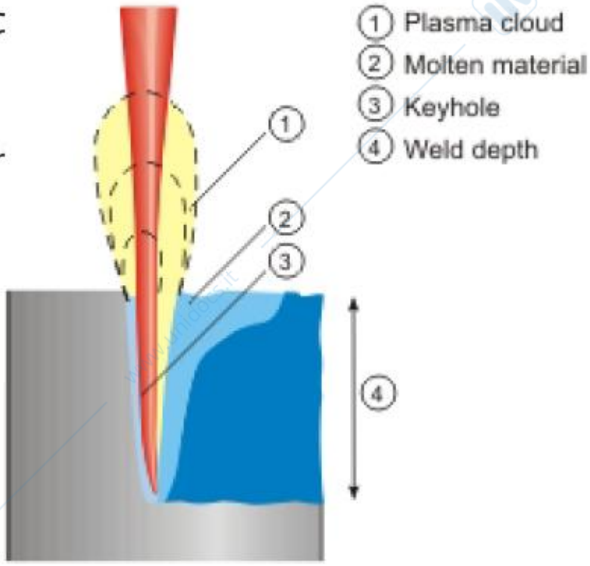


when the power density is insufficient to cause boiling - and therefore generate a keyhole -



KEYHOLE WELDING





Deep penetration welding

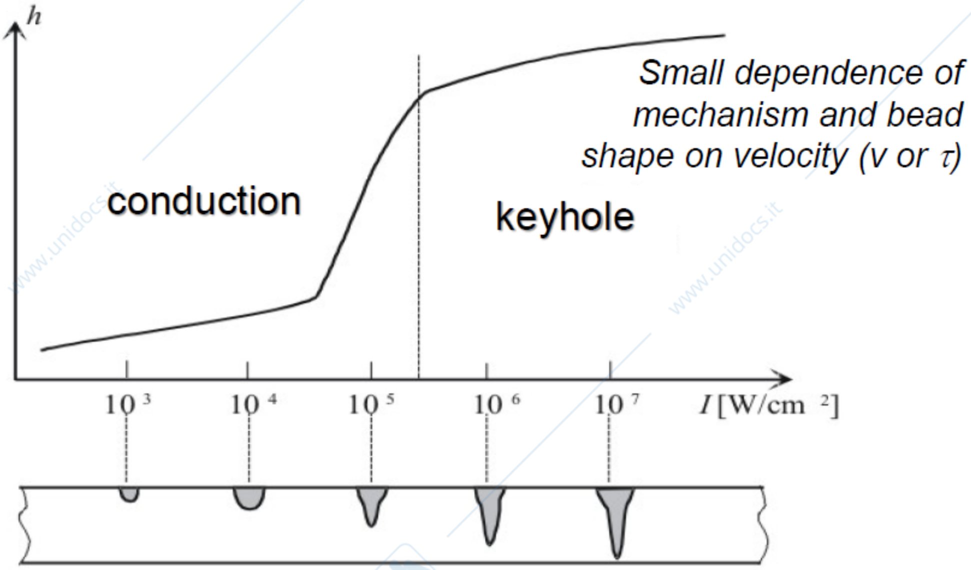
Keyhole: column made of plasma and surrounding column made of liquid. We will have a very deep penetration inside the material with a shape factor which is completely different from conduction welding. The shape of keyhole will depend on the power density and on the interaction time.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

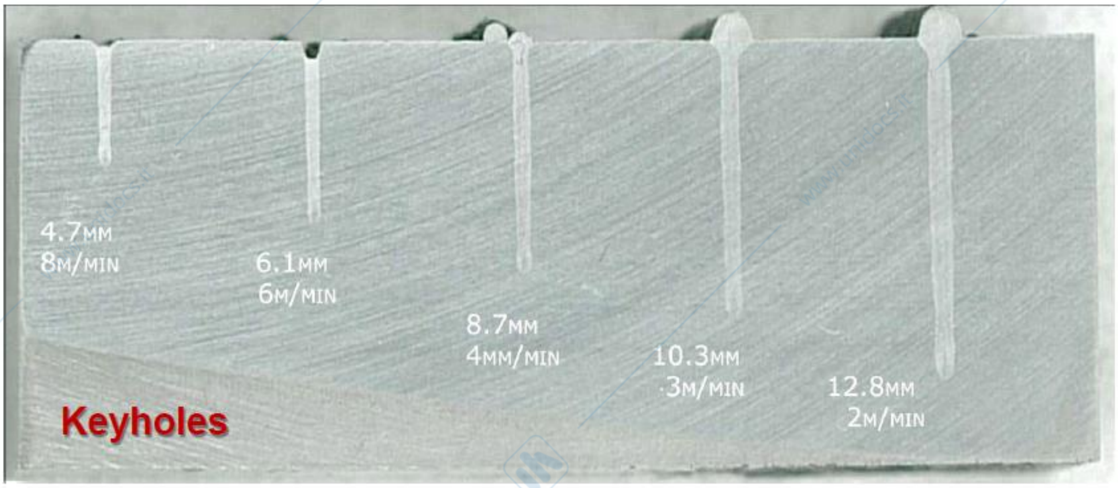
CRITICAL LIMIT BETWEEN CONDUCTION AND KEYHOLE WELDING

In the figure below, we can see the transition from conduction to keyhole welding for steels. Only by changing I, we can obtain the shift from the 2 operations. If you increase I, you generate vapor on surface, A increases instantaneously (material behaves like a black body), and you transform into plasma the column of vapor. While if the power density is lower, you will create a film of liquid, A will increase but there will be time for the heat to be conducted → conduction limit welding.



The shape of the bead depends on I

SPEED EFFECT



8 kW fiber laser
penetration test

Material: Stainless Steel 1.4301
Laser: 8 kW
Spot d_s: 330 μm

In the figure above, we can see for a given laser with a given power and a given spot size, how the travel velocity of the welding head influences the shape but especially the size of the welding seam (case of keyhole welding) on a stainless steel. In particular, the values of the penetration depth as the speed varies are compared. We can se that if we go slower, we increase the penetration depth (higher interaction time). In addition, we don’t only

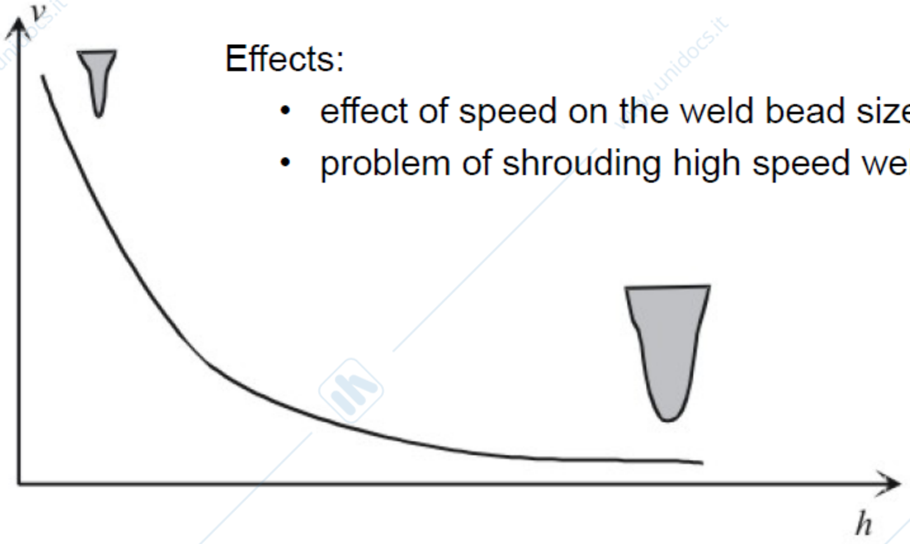
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

change the size but also the quality, for example on the top of the welding seam. Moreover, notice that if we go faster, we obtain a thinner welding seam with a thinner heat affected zone → if the sheet which we have to weld is thin, adopting a high speed of the welding head is convenient (suitable penetration depth and thin welding seam and HAZ). If we go slower the top bulge is larger because of we give more time to the less dense material to move upward.

In the figure below, we can see again this comparison in a graph: if we go fast h is little while if we go slow, h is high. Moreover, notice that if we go too much fast, we may have problems with the action of the shrouding gas → it becomes more difficult to obtain a proper protection.

Keyhole welding

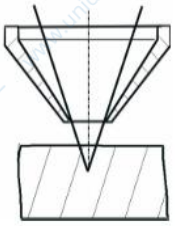


Effects:

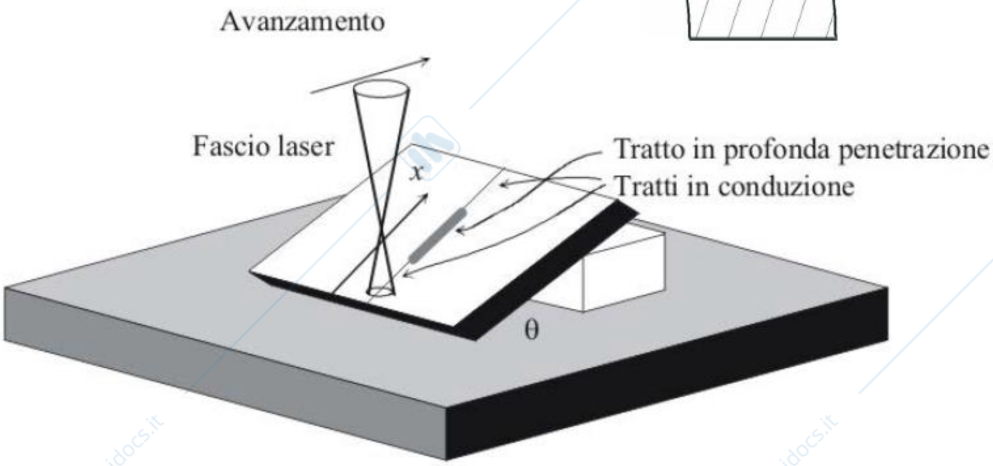
- effect of speed on the weld bead size
- problem of shrouding high speed welds

FOCAL POSITION

- Negative, within the workpiece
- Depending on the depth of field



$$\Delta z_{pdc,tech} = |x_{in} - x_{out}| \sin\theta$$



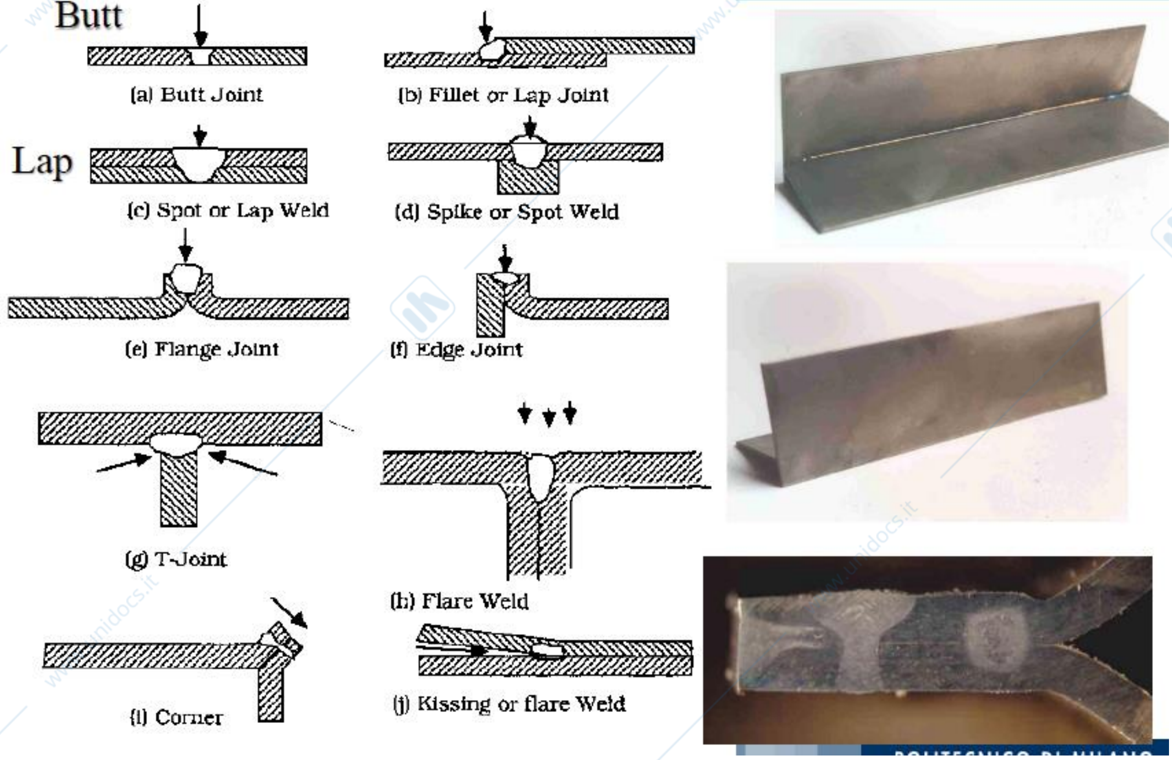
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

If the sheet is not flat and we don’t have an autofocus, we might switch from good to bad welding properties because we could go out from the waist region (we could exceed the depth of field obtaining a spot size too much large and thus a non-suitable power density).

JOINT GEOMETRIES

The 2 typical joint geometries are the butt joint and the lap joint. The lap joint can be in the fillet or completely overlapped. In butt joint positioning is more critical than in lap joint. In both cases it is convenient to have negative focus and it is convenient to have a gap between the 2 sheets. But, laser welding can also be remote: if we have a lens that can focus at high distance we can have the welding head far from the sheet, even 1 meter distant. In this case we can also think on welding regions of difficult access, laser is the only technology which can perform this type of welding (example: auto already assembled). The preferred possibilities of joint are the one which tend naturally to entrap the laser beam and also the reflective laser beam → we would like to have a gap between the 2 sheets and negative focus: the reflective beam will be absorbed by the material.

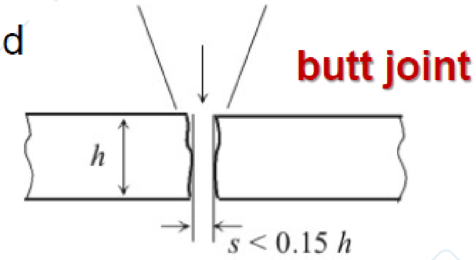


The gap that we have to provide in a butt joint depends on the application, but as an order of magnitude usually the gap is less than 15% of the sheet thickness. When we have a lap joint again it might be convenient to have a vertical gap. This is rather unpractical but it is generally required for example in zinc coated sheet which are typical of automotive applications, because gas will form → the risk is that we entrap the gas inside the weld, we may enclose bubble of gas between the 2 sheets: we lose the strength of our weld. In a lap joint the shrouding is quite difficult in the gap.

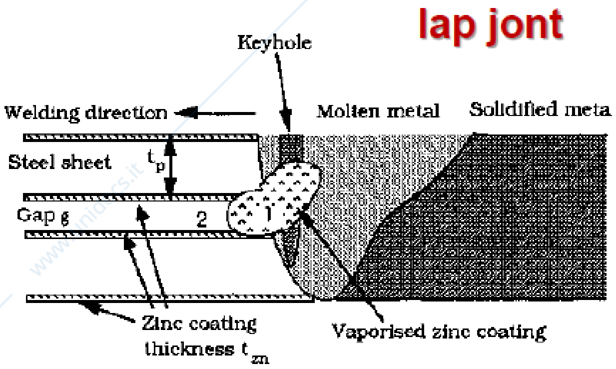
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

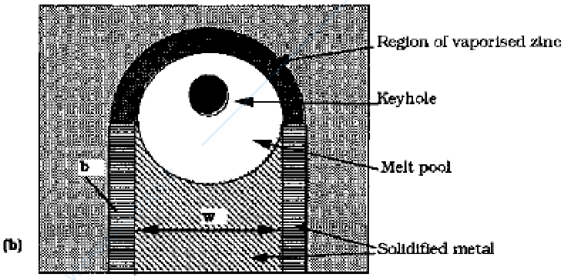
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

- Depends on the spot size and mode effect



- Essential in welding of zinc coated steels





Diagrams showing the welding of zinc coated steel with a small gap between the sheets for the exhausting of the high pressure zinc vapour generated during welding , (a) side view, (b) plan view.

SHROUDING GAS

The materials we want to cut will form vapor that will transformed into plasma, in order to be transformed they have to be ionized. The smaller is ionization potential the easier we will ionize the material and form the plasma --> for Aluminum we will create the keyhole more easily. But we can have plasma also thanks to the ionization of gas (shielding and shrouding), and we don't want because it will block the laser light and will diffract it in all directions dispersing power. So, we would like the gas not to ionize possibly. The best gas is helium since it is more difficult to ionize it because it has a high ionization potential; helium is expensive, we can use helium for top and other gases for sides. Whenever it is possible we can use CO2 which is the cheapest but has a low ionization potential or argon is a good trade-off between money and performance.

- **Aims**
  - To shroud
  - To blow away plasma
  - To protect lens

- **Shroud gas affects plasma formation**
  - Reaction of hot metal plasma from keyhole

High v (top shroud gas)

Ionisation Potential of Common Gases and Metals

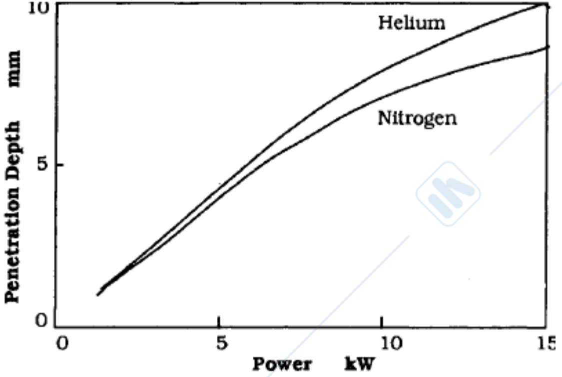
Material	1st Ionisation Potential, eV	Material	1st Ionisation Potential, eV
Helium	24.46	Aluminium	5.96
Argon	15.68	Chromium	6.74
Neon	15.54	Nickel	7.61
Carbon dioxide	14.41	Iron	7.83
Water vapour	12.56	Magnesium	7.61
Oxygen	12.50	Manganese	7.41

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

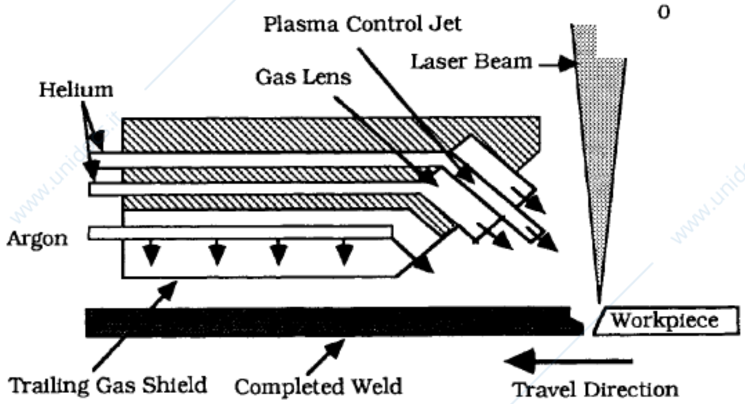
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

In general we have a gas feeding head which can even combine different ducts with different gas flows to have a better gas control quality.

- **Absorption of laser beam**
  - Temperature
  - Ionization potential

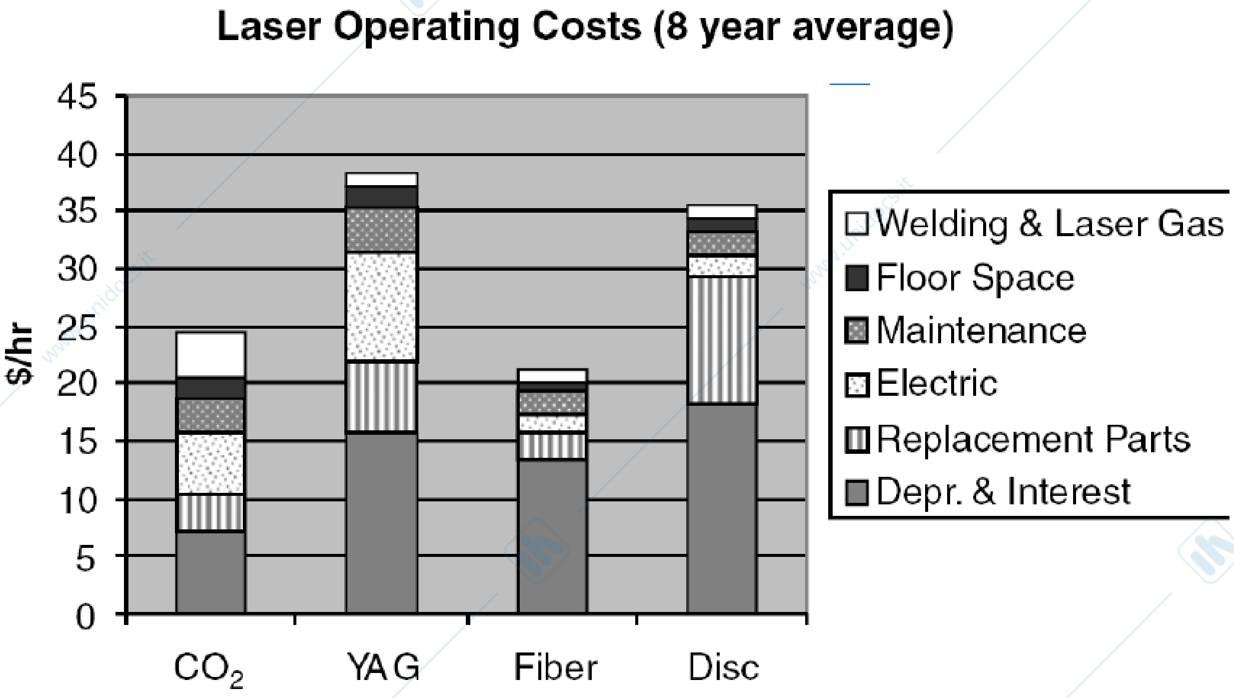


side blown gas jets



The shroud underneath the weld can be of a cheaper gas, e.g. argon, N_2 or CO_2

COST COMPARISON



*L. Quintino, A. Costa, R. Miranda, D. Yapp, V. Kumar, C.J. Kong "**Welding** with high power fiber lasers – A preliminary study", Materials and Design, 28, **2007**, pp.1231–1237

Some of these costs are not relevant when we want to design the process parameters, so from a technological point of view. Electric cost is important, because we can have several

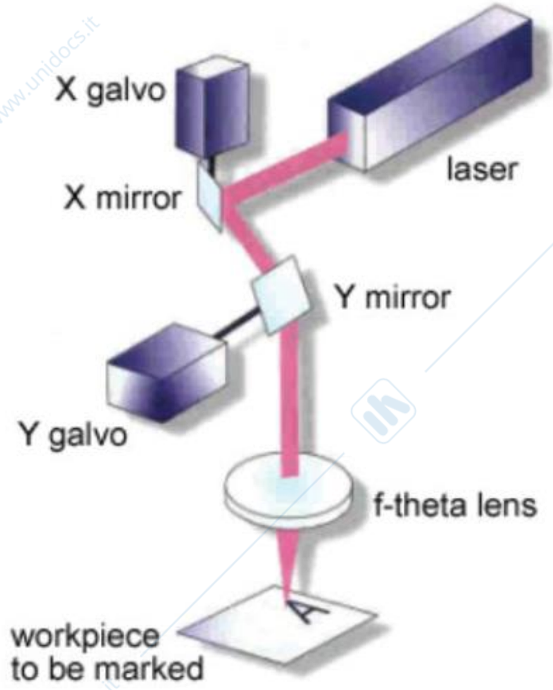
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

kW of installed power with low efficiency, also gas flow should be considered in the cost function. This picture has to be updated because is of 2007.

LASER MARKING

Any application which requires precise and fast scanning of the surface can be done with laser. Marking is a material removal process but only at a very shallow depth. We can change the position of 2 mirrors, by this combination we can obtain x and y axis. Mirrors are servo-controlled in close loop with galvanometric motors (by applying a electrical current to a coil we induce rotation of a member, it is very precise and fast). The area where we can deflect the ray without change the incident angle is not very high.



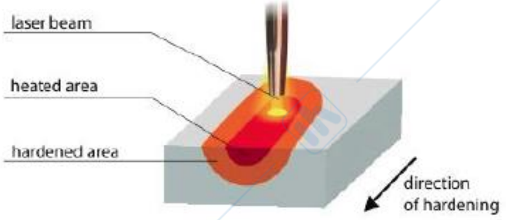
Galvo: high-resolution rotary motor with a mirror mounted

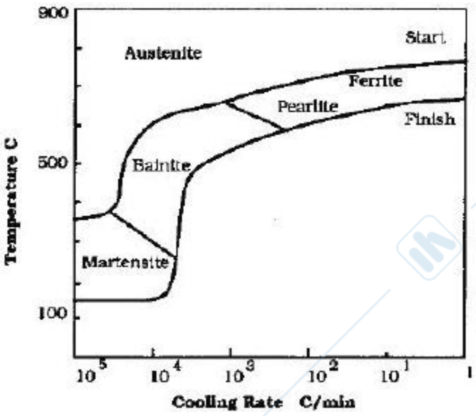
LASER HARDENING

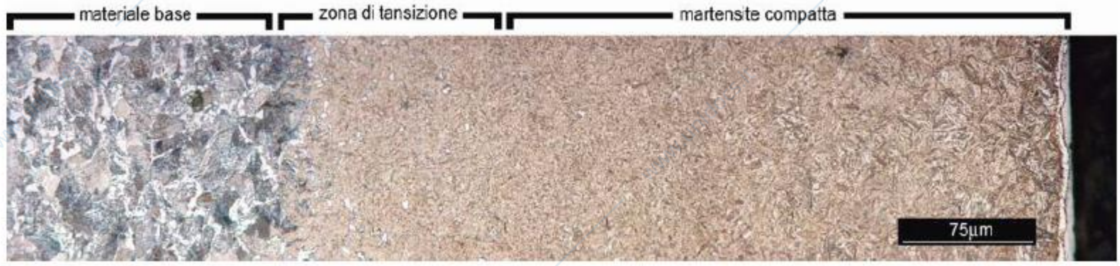
With the laser beam we can do surface treatments in general. We won't a melted pool now, we want isothermal curves that starts from the center of the beam. We need to control as usual I and tau, by changing them we can obtain different thermal treatments on the material. We can use also fast cooling in addition to laser in order to obtain a certain heat treatment. Laser treatment is used only for surface treatment, for hardening for instance the outer surface. Sometimes it is preferable a bad quality of the laser beam because in that way the power is not focused in the centre of the beam but is more homogeneous distributed. Moreover, sometimes we use a square shape of the laser beam in that case because every point in the path of the laser beam undergoes the same heat treatment.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

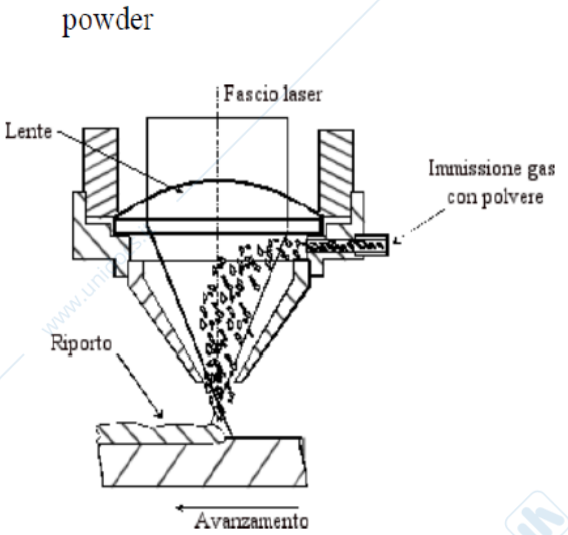
www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

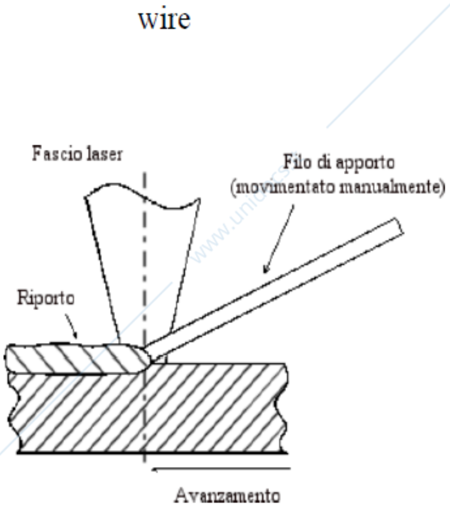






LASER CLADDING





Laser cladding is very important: it has used for repairing mostly. We can bring additive material on the surface of the workpiece by means of powder feeding or wire feeding; in both cases we need to convey the new material at the location of the spot. It can be a side flow or annular flow of powder grains, they will be converted by the laser --> powder grains are melted by laser and solidify on the surface. This technology is used also for coating, but the shape obtained is not very regular.
In addition, laser cladding by powder or wire was the starting idea for inventing additive manufacturing--> layer by layer you can deposit material, you can build row after row a

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

new material. DED: direct energy deposition --> we direct deposit some material where we want to, thanks to a laser beam (energy beam in general).

Directed Energy Deposition processes

Here (figure on the right) you want to obtain a divergence duct, this duct has been obtained through a laser powder deposition head. The ducts convey powder and some others the assist gas --> we want to melt the powder and to obtain its solidification on the material. This is very similar to welding, so we have all the problems that we have in welding (as oxygen). The surface roughness is comparable to sand casting (Ra=12 microns). Aspiration vents are used to take the grains wasted away from the chamber because they can create some problems, this wasted powder is in part recycled.

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari

www.unidocs.it - Appunti e dispense per superare i tuoi esami universitari