CO_2 Laser Workstation
Laser Maintenance
&
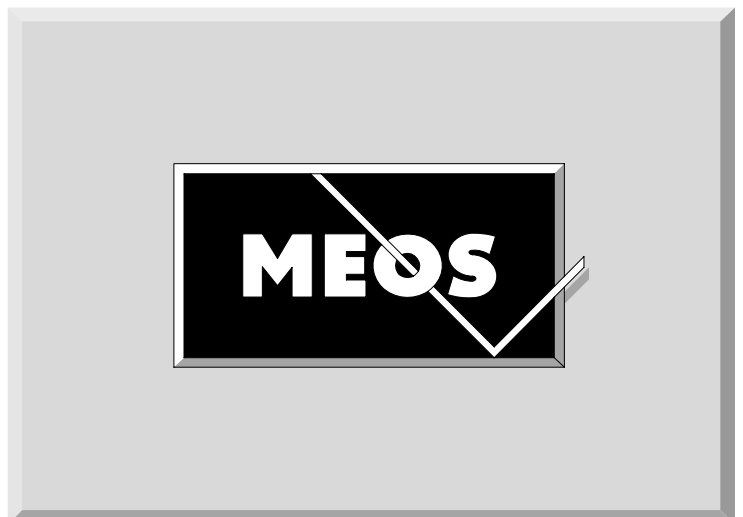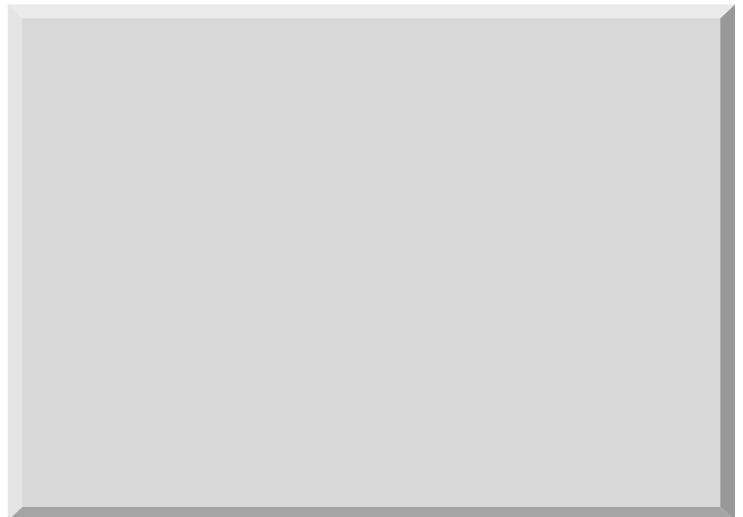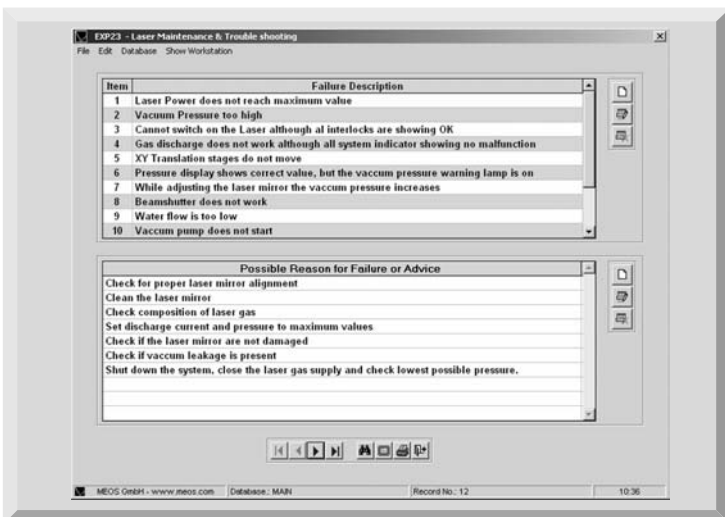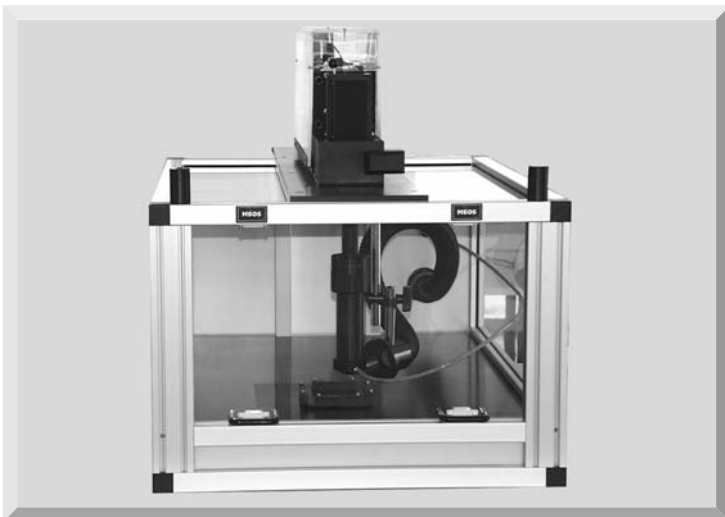# Trouble Shooting

Laser Gas Supply System

Laser System

Vacuum System

Water Cooling Sytem

XY Motion Control

EXP23 - Laser Maintenance & Trouble shooting

File   Edit   Database   Show Workstation

Item	Failure Description
1	Laser Power does not reach maximum value
2	Vacuum Pressure too high
3	Cannot switch on the Laser although al interlocks are showing OK
4	Gas discharge does not work although all system indicator showing no malfunction
5	XY Translation stages do not move
6	Pressure display shows correct value, but the vaccum pressure warning lamp is on
7	While adjusting the laser mirror the vaccum pressure increases
8	Beamshutter does not work
9	Water flow is too low
10	Vaccum pump does not start

Possible Reason for Failure or Advice

Check for proper laser mirror alignment
Clean the laser mirror
Check composition of laser gas
Set discharge current and pressure to maximum values
Check if the laser mirror are not damaged
Check if vaccum leakage is present
Shut down the system, close the laser gas supply and check lowest possible pressure.

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Table of Contents

1 Introduction

The CO_2 Laser, is undoubtedly considered to be the most important technical development since the beginning of the discovery of the Laser in 1961. Many types of Lasers were discovered and developed in the 60's. But no one had the idea until in 1964, C. Patel reported about a CO_2 Laser, of less than a milliwatt output power, having at its disposal an immense technical potential. Today, after more than 33 years of stormy Laser development, the CO_2 Laser forms an indispensable part of industrial production. In comparison with all other Lasers, the CO_2 distinguishes itself by its much higher efficiency and extremely high power output. So much so, that the limit of the output power is imposed only by the limits of destructibility of the optical resonator's components. The present technology permits the Laser to achieve output powers of up to 20kW. With 10kW power, one can cut through a centimetre thick steel sheet. CO_2 Lasers of under 100 Watt power output have however achieved the most frequent application usage. The CO_2 Lasers wavelength is 10.6 μm and falls in the range of infra-red radiation, which is also referred to as thermal radiation. The interaction of this radiation with matter is thus thermal. The coherence of the Laser beam permit it to be focussed on a diameter of 10μm. Consequently, the CO_2 Laser makes it possible to concentrate extremely high heat radiation onto to the exact point of a particular component. Depending on the Laser power, different effects are achieved e.g. simple heating for soldering purpose or thermal colouring for inscriptions on plastics. At higher Laser power, the material local melts and with the help of a gas (e.g. oxygen) co-axial to Laser beam is blown and the steel is cut or bored. A further application area is the Laser hardening. It is possible e.g. crankshafts or valves for internal combustion engine to produce local hardening, as it would have been difficult or impossible for the traditional methods. Also in the medicine there are various applications to be named e.g. operation of high blood organs, such as liver, due to high cost of blood stemming and always involved with high risk. On the contrary, the CO_2 Laser beam burns the operational area, coagulates the cut and blocks the blood vessels at the same time. When Patel discovered the CO_2 field in 1961, it was not a pure co-incidence. As a co-worker of Bell Telephone Laboratories, he was a witness to the discovery of the first gas Laser of the Helium - Neon Laser. In a very beautiful essay by Patel in the Scientific American (High Power Carbon dioxide Lasers 1968) he writes:

„The output from the carbon dioxide Laser at 10.6 μm, although invisible to the eye, is just as devastating as that from any other powerful Laser. The thermal applications of the carbon dioxide Lasers command considerable industrial interest. More important, however, are the non-thermal applications of the carbon dioxide Laser. These potential applications include optical communications both on the earth and in space. The main attraction here is the low-loss optical „window" that exists between eight and 14 microns for transmission through the earth's atmosphere. The high efficiency and high power of the carbon dioxide Laser at 10.6 μm make them ideal candidates for such applications."

This small statement makes evident the interest of the Bell Telephone Laboratories at that time. The specific research on Infra-red Laser is explained so convincingly by Patel ,that once again a part of his essay is quoted here:

„I should like to explain now how it was I came to build and operate the first continuous-wave molecular-gas vibrational-rotational Laser at Bell Laboratories a few years ago. In the course of our investigation of Laser action in atomic gases it became clear that if the aim was to obtain large power output in the infrared region (that is, at wavelengths longer than a few microns), the atomic gases were far from the ideal system. This is primarily so because for most atomic gases the electronic energy levels between which infrared transitions can occur are situated close to the atomic ionisation limit - far above the ground state of the atom. As a result the atom has to be excited to a very high energy level in order to produce Laser action, which in turn results in the emission of a photon with a comparatively small amount of energy. Thus the use of atomic gases results in a low quantum efficiency and consequently a low working efficiency. Such a system has another very serious drawback. Close to the ionisation limit of an element the energy levels corresponding to different electronic configurations are situated in a very small energy range; as a result electron-impact excitation, which is the mechanism for producing Laser action in gas discharges, would be highly nonselective and the population density of atoms in the upper Laser level would be very small. This will further limit the power output and result in an even lower working efficiency, since a significant fraction of the energetic electrons capable of exciting atoms to the upper Laser level are lost in exciting atoms to other levels nearby. Typically an atomic-gas Laser operating at a wavelength of about 10 microns produces only a few milliwatts of power and has a working efficiency of about 0.001 percent. The situation is entirely different when one is dealing with molecules; the vibrational-rotational levels belonging to the electronic ground state of a molecule are ideal for efficient and powerful Laser systems in the infrared region. The vibrational levels of the electronic ground state are very close to the ground level of the molecule and thus the Laser photon energy is a sizeable fraction of the total energy needed to excite the molecule from the ground state to the upper Laser level. The result is a very high quantum efficiency compared with that of an atomic-gas infrared Laser. In addition, since the vibrational levels are close to the ground state of the molecule, almost all the electrons present in a discharge will be effective in the required excitation process. This fact ensures a high working efficiency as well as a high power output, because now one can obtain a large population density of molecules in the upper level.

It was on this basis that I originally decided to investigate the possibility of Laser action using the vibrational-rotational transitions of the electronic ground state of carbon dioxide."

In the following examples the content of the citation shall be explained further. We will use the well-known Helium-Neon Laser and discuss its efficiency. Patel uses two efficiencies - the quantum efficiency and the working efficiency or total efficiency. We denote the first by η_{quant} and the last by η_{tot}.
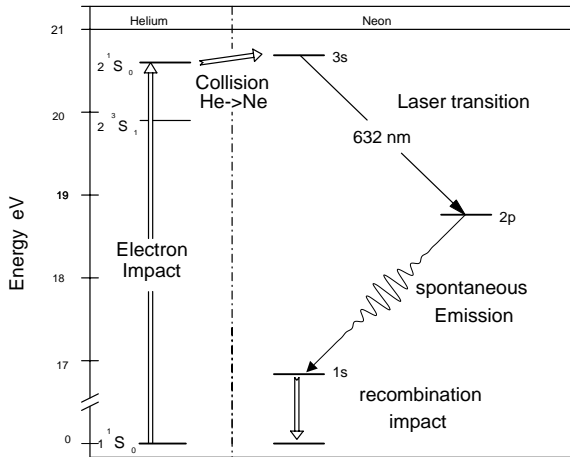

Fig. 1: Laser cycle of the Helium Neon Laser for the visible line at 632 nm.

The quantum efficiency is defined as the ratio of the energy of the photon produced for the Laser transition to the excitation energy. In the example according to Fig. 1, energy of the produced photons is the energy difference between the Laser output level 3s and the Laser end level 2p, and the excitation energy is the energy difference between the 3s and the ground state, with regard to the energy of the state 3s (20,7,eV) We use the equivalent of 1eV=8056.7 cm^{-1} or 1.97eV respectively. With this, the degree of quantum efficiency results in

$$\eta_{quant} = \frac{1,97}{20,7} \cdot 100 = 9,5\%$$

It means that 90.5% of the excitation energy is already lost. This efficiency is of pure theoretical nature. The optical resonator as well as the discharge tube cause unavoidable additional losses. Further, the common disadvantage of each atomic gas Laser excited by gas discharge is that its Laser output level lies at a high energetic level. It means that the other energy state always exist in its surrounding, excited likewise by the electron impact. A considerable part of the excitation quantum is lost through this for the actual Laser cycle. Therefore, the total efficiency is decided essentially from the selectivity of the excitation. Let us assume, e.g. a Helium Neon Laser used today, in which about 20 Watt of electric power is required to produce 1 mW of Laser power. This comes to a total efficiency of :

$$\eta_{tot} = \frac{0,001}{20} \cdot 100 = 0,005\%$$

If we want to produce Laser radiation with the wavelength of 10.6 μm approx. (10.6 μm-corresponds to 943.4 cm^{-1} or 0.12 eV) We require energy level distanced from each other by only about 0.12 eV. The distance of the

atomic level is reduced with increasing excitation level of the atom. In a borderline case of ionisation, the level is continuously distributed. Thus one such Laser would still have a bad quantum efficiency, because on the one hand, the excitation energy is very high and the energy of the photon is comparatively smaller by a wave-length of 10.6 μm with 0.1 eV. For further complication, there exist still a higher number of energy levels in the surrounding higher energy levels which is populated also by the electron impact excitation. This in turn, reduces the total efficiency still further. An atomic infra-red Laser, excited through discharge, with high output power and reasonable efficiency cannot be realised by this way. Patel, therefore turned to molecular Lasers. Contrary to the atomic energy states, for molecules there exists a far greater variety of energetic states which are suitable for the optical transition and thereby in the construction of the infra-red Laser. Before we discuss the actual Laser active CO_2 molecules, let us take a small trip to Molecular Physics to understand the concepts such as vibration and rotating states of the molecule. So much before hand, the CO_2 Laser is based upon the optical transition between vibration transitions in the electron ground state of the CO_2 molecules.

2 From the Atom to the Molecule

In this paragraph, we shall discuss the question, of how a molecule originates from two isolated atoms and the new energy states that are to be built. First of all, we deal with this through the example of only two similar atoms, as e.g. the Hydrogen. It exists in the rule only as H_2 and not atomic. Moreover, we deliberately draw the two H_2 atoms close to each other. We describe through this the reduction of the distance of both the nuclei to each other. As the nucleus of each H_2 atom consists of only one proton, it is assumed that because of the Coulomb's force, both the nuclei would not come close to each other when there are no electrons. If the atoms are drawn closer, then the state of the undisturbed energy level splits up in different energetic states. The number of the newly emerged states corresponds to the number of exchangeable electrons (Fig. 2).
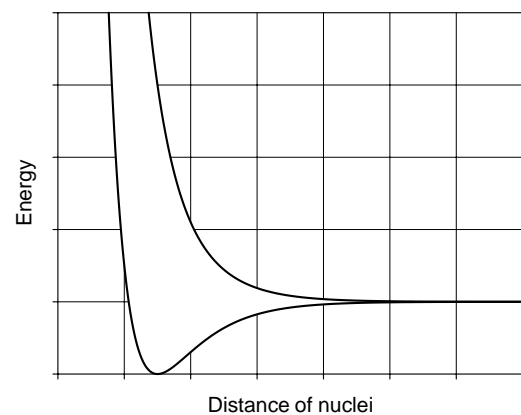

Fig. 2 : Potential energy curves of the interaction of two Hydrogen atoms.

One of the two curves possesses a local minimum for a certain distance of the atoms. Certainly the atoms will get closer to each other without any force and remain in this

potential mould. That is also the reason for the Hydrogen appearing always molecular as H_2 under normal conditions. The second curve does not possess such a distinct uniqueness. The curves differentiate themselves through the fact that for the binding case the spins of both electrons were anti parallel ($\uparrow\downarrow$)and for the non-binding state parallel ($\uparrow\uparrow$).Obviously, anti-parallel aligned electron spins generate a force of attraction which neutralise the Coulomb's force of repulsion of the nucleus. It is fascinating to imagine the effects of electrons as ambassadors at this stage. Through the advent of an unknown atom at the moment, the outer electrons receive the 'first wind from the thing" and start to overlap significantly; in this attempt an electron leaves its nucleus and goes into the track of another atom, rotating there for a couple of rounds before returning back again. When everything is in order, i.e. the orbits of other electrons are aligned, then it befits the new arrival. Through the activity of these "inquisitive" electrons, the nuclei can now get closer. This continues till the nuclei have come close by the minimum tolerable distance. In the meanwhile, now it is difficult to know which electron belongs to which nucleus. But nevertheless, a hard rule is applicable to the otherwise liberal electrons: My energy level should be used by an electron exclusively which possesses opposite aligned spin (Pauli's principle). Serious are now forewarned not to assume that these are possibly masculine or feminine electrons, but who knows....

2.1 Molecular vibration

We return with certainty to unerring physics. We have established that the two isolated atoms get close despite the repulsive force of the nucleus, when electrons in the outer shell of one nucleus can exchange with the electrons of other nucleus. This results in a linkage established through reciprocal exchange effect of outer electrons. The atoms bound in such a manner are called molecules.
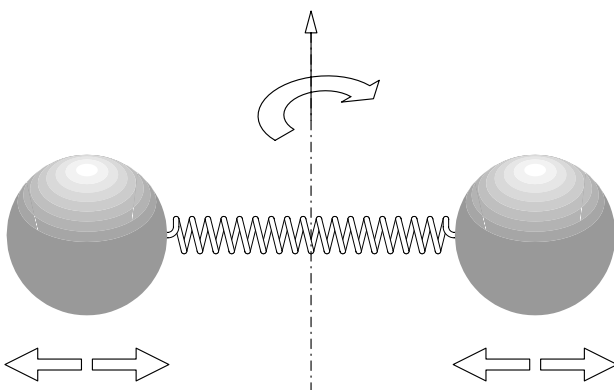

Fig. 3: Elastic bond of the two atoms

The molecule acquires energy states depending on the distance of two nucleus. The molecule can exist apparently for different nucleus distances. We further assume that the bond between the nuclei is not fixed, but flexible in a certain area. On the other hand, it suggests an assumption that there exists an affinity between the nuclei when they come closer for the first time. This could be described through an elastic spring. (Fig. 3).Now one can further imagine

that in such a formation, supply of energy can cause vibration to occur. In the same manner, molecular rotation takes place around the symmetry axis. However, we shall describe this in more detail in the latter chapters. Now the question which energy state would a molecule take when such energy is supplied to vibrate has to be answered. From classical mechanics, we know the model of linear harmonic oscillation. We are modifying the model of Fig. 3 into a model with only one mass. The masses of both the atoms are combined into a reduced mass M (Fig. 4).
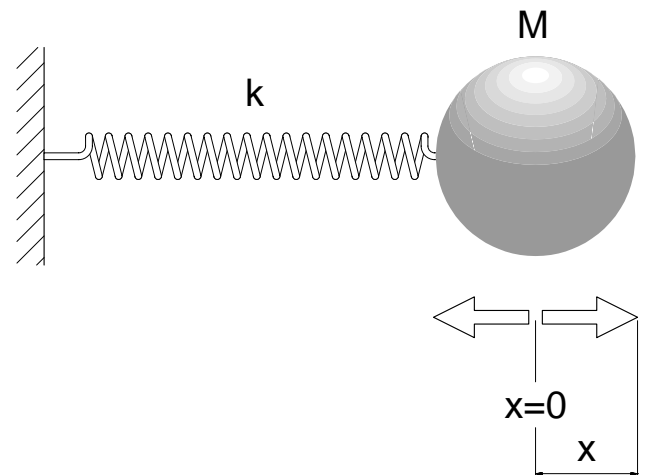

Fig. 4: Linear harmonic oscillation

The elastic spring possesses the spring constant k and we assume the stationary position of Mass M by $x=0$ and the elongation thereby as x. According to Hooke's law, the force F, which is required to produce a displacement x is:

$$F = -k \cdot x$$

Now we again assume that we have an ideal system with no outer friction and no inner loss, so the mass M oscillates till eternity with the frequency:

$$\nu_0 = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{M}}$$

We get the potential energy U from the relation:

$$\vec{F} = -\nabla U$$

as:

$$U = \frac{1}{2} \cdot k \cdot x^2 = 2\pi^2 \cdot M \cdot \nu_0^2 \cdot x$$

The result tells us that the energy of a classical harmonic oscillator can assume any value. However, this is contrary to the experimental experience gained by the measuring of the vibration spectrum. Here, it is shown that there exist no "sharp" lines, therefore no continuation as it is obvious in the model of the classical harmonic oscillator. Now, what is wrong with our model ? Either such a model is false or we have overlooked the side constraints present in the atomic but absent in the used macroscopic system. Also, classical mechanics understands a system which assumes

only the discrete energy value e.g. a restrained chord or a drum skin under tension. Here the side constraints are so many that the chord is tensed on two sides. However, which side constraints are valid for a molecule, whose atoms carry out a harmonic oscillation or vibration. Quantum mechanics gives the answer. Certainly, we cannot discuss its contents at this stage as it will simply be too much to mark the quantisation of the harmonic oscillation and to use its result in order to understand the energy equation of diatoms and thereafter of its CO_2 molecules. In classical mechanics, we indicate the total energy E of any system as:

$$E = E_{kin} + U$$

or.

$$\frac{m}{2} \cdot v^2 = E - U \qquad \textbf{Eq. 1}$$

De Brooglie has proved with his famous formula:

$$\lambda = \frac{h}{m \cdot v}$$

h is the Planck's constant, v is the velocity and m the mass that a wave can be assigned to. This wave with frequency v propagates with speed u:

$$u = v \cdot \lambda = \frac{h \cdot v}{m \cdot v} \qquad \textbf{Eq. 2}$$

Schrödinger concludes, that if this is so, then it must exist an equivalent for the common valid classic wave equation with $E(x,y,z,t)$ as amplitude of an oscillation and its speed of propagation:

$$\Delta E = \frac{1}{u^2} \cdot \frac{\partial^2 E}{\partial t^2} \qquad \textbf{Eq. 3}$$

namely, a wave equation for a wave of matter:

$$\Delta \Psi = \frac{1}{u^2} \cdot \frac{\partial^2 \Psi}{\partial t^2} \qquad \textbf{Eq. 4}$$

A hint, in order to derive the new wave equation based on equivalent of Mass and Energy, Schrödinger selected the notation

$$\Psi(x, y, z, t)$$

instead of

$$E(x, y, z, t).$$

As we are interested her at first, only in the stationary states we may separate the amplitude Ψ into time and space dependent terms.

$$\Psi(x, y, z, t) = \psi(x, y, z) \cdot e^{-2\pi i v t} \qquad \textbf{Eq. 5}$$

In Eq. 4 Schrödinger inserted Eq. 1 and Eq. 2 in combination with Eq. 5 he obtained:

$$\Delta \psi + \frac{8\pi^2 m}{h^2}(E - U) \cdot \psi = 0 \qquad \textbf{Eq. 6}$$

Differential equations of this type are well known from the solution of oscillating systems e.g. a tensed string. Also the inclusion of the boundary conditions leads to discrete solutions with regard to the frequency of the vibrating chord. That means that a tensed chord can vibrate only

with certain frequencies (eigenfrequencies), namely, on its fundamental and the corresponding higher order frequencies. The solution, in view of the attributes of a special system are also characterised by eigenvalues. The solutions for Ψ are called eigenfunctions and for the energy state E as a eigenvalue of the energy. The difference in the solutions between the Schrödinger and the classical equation lies in the fact that the eigenvalues of the energy has been quantisised as *(E = hv)*. Subsequently the discrete eigenvalues are also quantisised as:

$$E(n) = n \cdot h \cdot v$$

That means the discrete energy states *E(n)* of a quantum mechanical system are integral to *hv*. The energy quantum itself is on the other hand v many times over the Planck's elementary action quantum *h*. The eigenvalue for the energy state of a classical system are integrals of the lowest base energy Eo, whereby Eo is bound to no further quantisation.

$$E(n) = n \cdot E_0.$$

What consequences does this short flight into quantum mechanics have on our diatomic molecule ? If we want to know about the new energy states, then we need to solve the Schrödinger equation with the external constraints in our system, namely the potential energy *U*.

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{8\pi^2 M}{h^2}(E - 2\pi^2 M \cdot v_0^2 \cdot x^2) \cdot \psi = 0$$

We want to leave here the presentation of the solution methods, as it is found to be dealt with thoroughly in almost each text book on atom and molecular physics. The solution is:

$$E = h \cdot v_0 \cdot \left(n + \frac{1}{2}\right) \qquad \textbf{Eq. 7}$$

Here n is an integer. While it is used for the characterisation of oscillation or vibration, we change the sign from n to v (not to be confused with speed v)
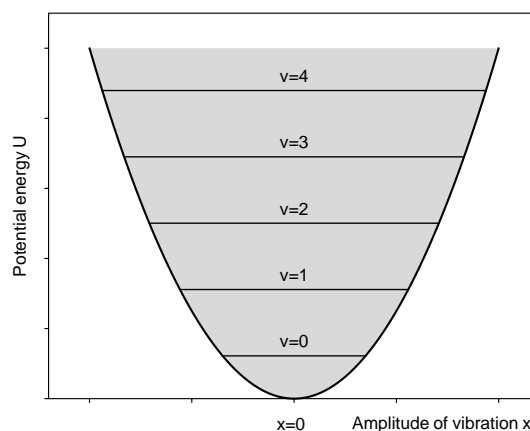

Fig. 5: Energy eigenvalue of the linear harmonic Oscillator

In Fig. 5, the potential energy as well as vibration energy states are shown. According to this, the molecule, though

not in vibration, possesses an energy for this ground state of:

$$E\left(v=0\right)=\frac{1}{2}\cdot h\cdot \nu$$

For interpretation of this zero point energy, (by the way, a popular test question) Heisenberg's uncertainty principle is used in the form:

$$\Delta p\cdot \Delta x\geq h$$

The energy will then be zero if the mass stays always by *x=0* (Fig. 5). Then the mass is localised exactly and violates due to *Δx=0* the above uncertainty principle.

A further interesting statement can be derived from Eq. 7. The energy difference of two different vibrations level is

$$E\left(v+1\right)-E\left(v\right)=h\cdot \nu_0=\frac{h}{2\pi}\cdot \sqrt{\frac{k}{M}}$$

Due to this, the energetic distance between the two neighbouring vibration levels is determined by the size of the vibrating mass. Significant differences arise for very small masses. This in an important corresponding principle which shows the transition from classical mechanics to quantum mechanics. Now, we would have almost completed the discussion of the vibrational state of a di-atomic molecule, if the potential energy *U* of the molecule was actually a pure quadratic function as in Fig. 5. That is, approximately only in the field of small vibration quantum numbers. A refinement and with that, an improvement of the interpretation of spectroscopy measurement is derived when the Morse's equation:

$$U(x)=D\cdot \left(1-e^{-ax^2}\right)$$

with

$$a=\sqrt{\frac{k}{2D}}\ .$$

is inserted in the Schrödinger equation. Then one gets the proper value of the vibrational energies:

$$E\left(v\right)=h\nu_0\cdot \left(v+\frac{1}{2}\right)-\frac{h^2\nu_0^2}{4D}\cdot \left(v+\frac{1}{2}\right)^2\ .$$

This solution describes the reality more accurately. Therefore, the energetic distance of the neighbouring vibrational levels is no more constant, but lowers itself more and more for higher quantum numbers of v. The density of the vibration state is increasing close to the disassociation boundary. Above this boundary, the molecule breaks into two atoms again and therefore the molecular vibrations no longer exist.
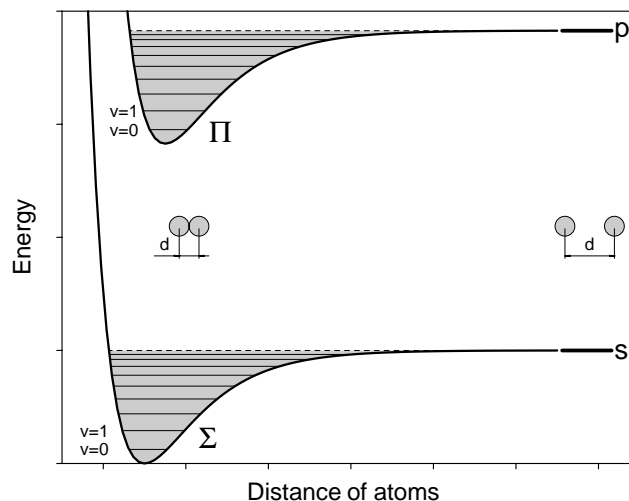

Fig. 6: Vibration states in a bi-atomic molecule

The upper curve shows the potential curve of the molecule which is created through the production of two atoms from excited atomic states. The lower curve emerges from the forming of a molecule by two atoms in the ground state. One of the interesting advantages of the CO_2 Laser consists of the fact that the Laser transition takes place only in the molecular ground state. So the special features of the electronic excited molecules state shall not be further dealt with here.

2.2 Molecular Rotation

In the beginning of the chapter on molecular vibration, it was laid down that besides vibration, a molecule can also execute rotation. This leads to a further number of energy states.
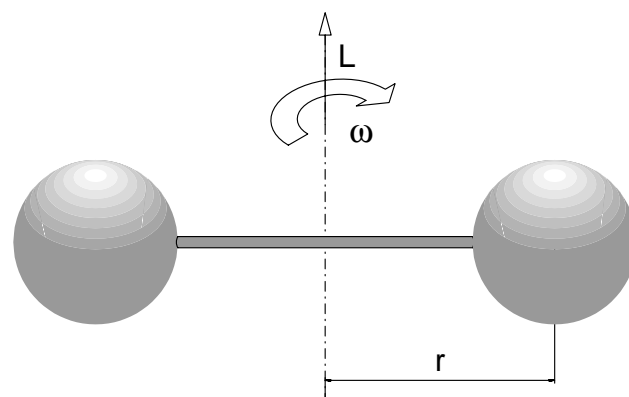

Fig. 7: Molecular rotation around a space axis

Here we want to give the result of the quantum mechanics calculation. This derivation is represented in turn in every fundamental work of molecular Physics.

$$E_{rot}=\frac{h^2}{8\pi^2\cdot I}\cdot J\cdot \left(J+1\right)$$

One also preferably uses the following representation:

$$E_{rot}=h\cdot c\cdot B\cdot J\left(J+1\right)$$

Here the abbreviation *B* stands for the rotational constant:

$$B = \frac{h}{8\pi^2 \cdot c \cdot I}$$

This abbreviation is therefore meaningful, because by choosing its dimension in cm^{-1}, the measured rotation spectrum can be taken directly. *I* is the moment of inertia of the molecule and c is the speed of light.
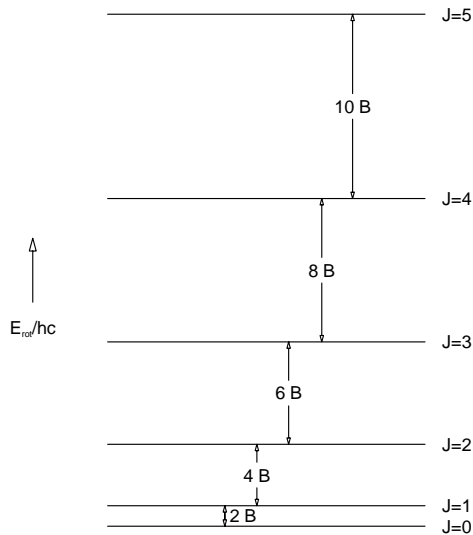

Fig. 8: Energy states due to the rotation of the molecules and the optical state with $\Delta J = \pm 1$

In the first approximation we assume that the vibration and the rotation do not disturb each other, so that we can give the total energy of the molecule in the ground state as the sum of the vibrational and the rotational energy:

$$E_{ges} = E_{Vib} + E_{Rot}$$
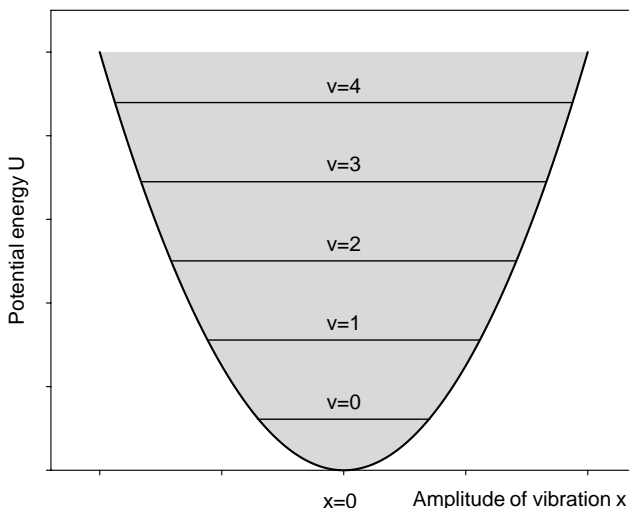
Fig. 9: Vibration and rotation energy state of a molecule for its electronically ground state

2.3 Selection rules of the optical transition of a molecule in its ground state

An optical transition occurs when the molecule during the transition from one state to another either emits a photon or absorbs it.

$$E(v', J') \rightarrow E(v'', J'') \pm \text{Photon}$$

Only such transitions which conform with the laws of conservation are allowed. The energy and pulse conservation must be ensured. From the fact that the photon possesses an impulse of the value:

$$P = \frac{h \cdot \nu}{c}$$

The absorbing or emitting molecule must take or release a pulse. This gives us the rule of selection with regard to the rotational quantum number *J*

$$\Delta J = J'' - J' = \pm 1$$

Regarding the selection rule of vibrational quantum number v, there are no strict rules. Only the probability of the vibration transition can be different. Transitions of the kind:

$$E(v'', J'') \rightarrow E(v', J') \text{ with } \Delta J = -1$$

are characterised as R-branch and those transitions with $\Delta J = +1$ as P-branch (Fig. 10).
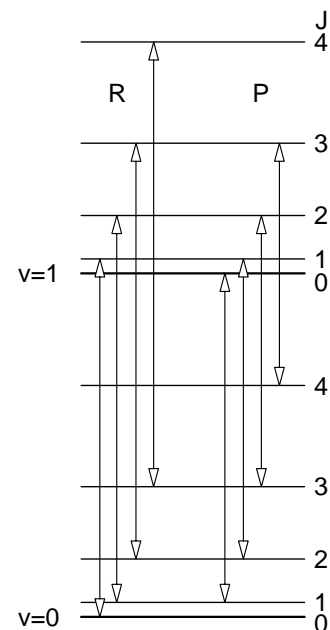

Fig. 10: Permitted optical vibrational rotational transitions

Towards the end of this chapter, it should be mentioned that the vibrational rotational transition within the same electronic state of a homo-nuclear molecule (O_2, H_2, etc.) are not permitted. Because due to the charged symmetry, no change occurs in the electric dipole momentum as it is necessary for the emission of radiation. The situation of molecules, made from different nuclei is different.

3 The CO$_2$ Molecule

The analysis of the possible energy states cannot be practically done with the Schrödinger equation, because the resulting differential equations become so complex that a complete solution is still not known. Now the following model is therefore, an interpretation of the spectroscopic data in view of the quantum mechanical facts of a molecule. The model is based upon the assumption of a stretched molecule, namely, that the two oxygen molecules are arranged around a centre which is taken from a carbon atom. The bonding between the atoms in the first approximation is elastic. This model can be arranged by three vibration modes.
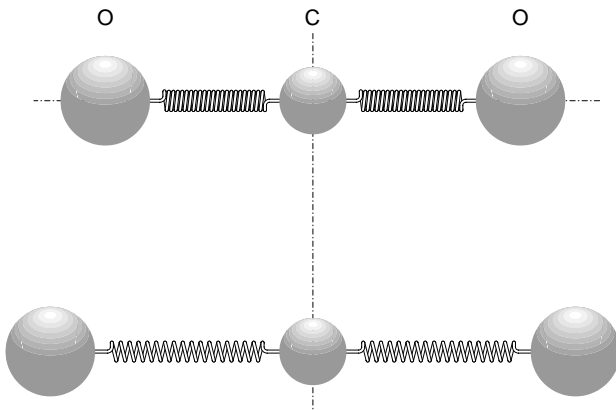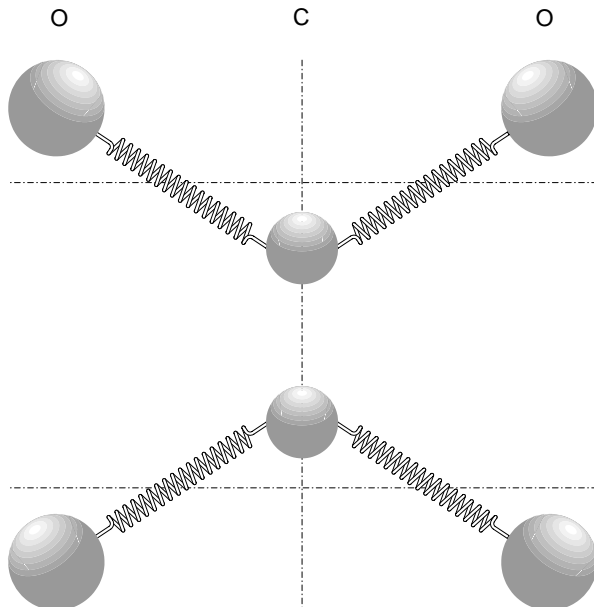

Fig. 11: Symmetric vibration, Mode ν_1 (ν,0,0)

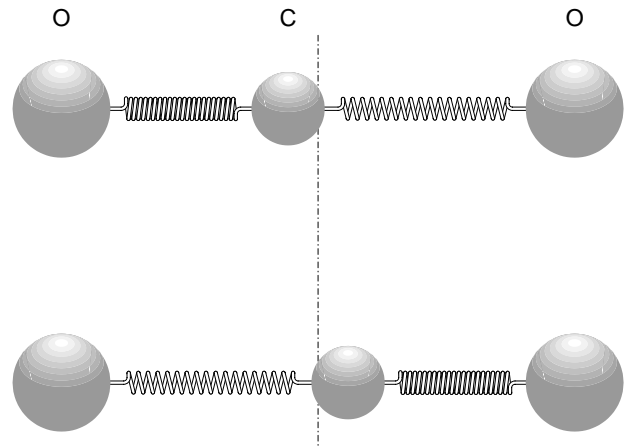**Fig. 12: Bending vibration, Mode ν_2 (0,ν,0)**

Fig. 13: Asymmetric Vibration, Mode ν_3 (0,0,ν)

To denote the vibrational state of the CO$_2$ molecule, a set of three components are used in the data, namely:

$$\left(n_1 \cdot \nu_1, n_2 \cdot \nu_2, n_3 \cdot \nu_3\right)$$

or simply:

$$\left(n_1, n_2, n_3\right).$$

For each fundamental vibration there exists molecular rotation which are characterised by the quantum number J.
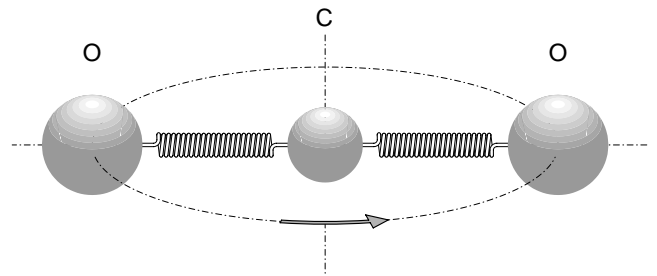

Fig. 14: Rotation of a CO$_2$ - molecule

The complete description of such a state goes as:

$$\left(n_1, n_2, {}^{J}n_3\right).$$

In Fig. 15, some of the vibration and rotation states for the basic vibration mode of the CO$_2$ are shown. However, there still exists a number of states which originate from the mixing or hybridisation of the fundamental vibrational mode. The transitions in connection with the CO$_2$ Laser take place within the fundamental vibrational mode. They are counted as the so-called regular band. Further, one should consider that due to the symmetries in the CO$_2$ molecules, there exists for the ν_2 state only rotational states with even and for ν_3 state only with uneven J quantum numbers. The Fig.15 shows the transition $(00^10) \Rightarrow (10^00)$ and $(00^10) \Rightarrow (02^00)$. The wavelength of the band edge is given, that means that the transition from $(00^01) \Rightarrow (10^00)$ corresponding to $(00^01) \Rightarrow (02^00)$, though prohibited, the data serves the spectroscopic notation. The permitted transitions are given again in the following figures.
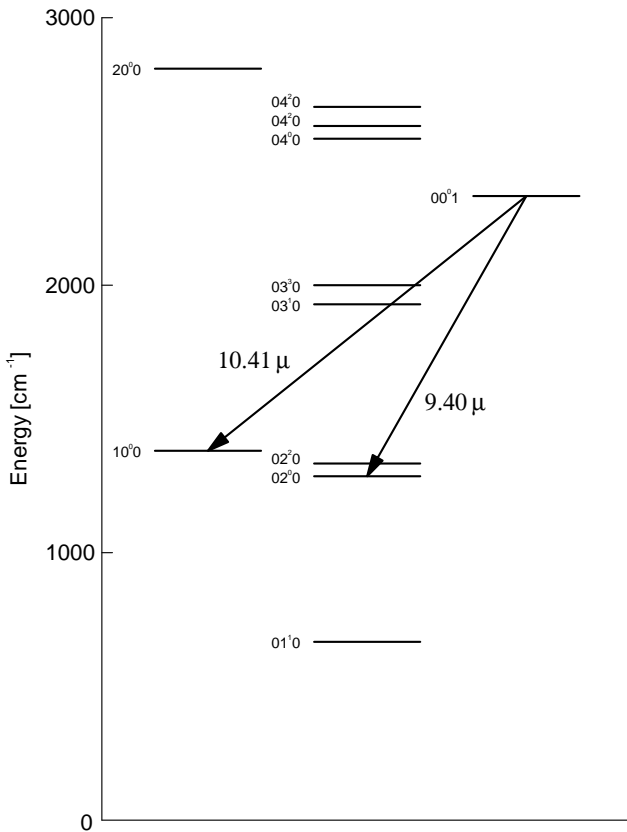
Fig.15: The most important transitions in vibration-rotation energy scheme of the CO_2 molecule

excited molecules are available. The life time of the vibrational state (001) i.e. the time taken between the excitation and the spontaneous emission of a photon amounts to 1 msec approx. During this period around 10^7 impacts per second with the other excited molecules take place, so that the rotation quantum number of a molecule changes continuously. In statistically means, its yields are as shown in the Boltzmann distribution in Fig. 16. At the temperature of 400° K. The most frequently occupied state is J=19. This is also the initial level for the Laser transition with a wavelength of 10.6 μm. Apart from this, there are a further number of transitions, some of which are given in Table 1.

(001)	$\Rightarrow$	*(100)*	
J''		*J'*	*P*
1		2	P(2)
3		4	P(4)
5		6	P(6)
n		n+1	
19		20	P(20) (10.6 μm)

Table 1: Permitted transition of the P-branch

The transition P(20) will interest us because this is the transition in which the Laser oscillation should be produced. Though there still exists the R-branch, it is not essential for the understanding of the Laser process. In the Fig. 17, a section of the spectrum is shown which once again explains the state of the P(29) transition.

Fig.17: Fig. 17 Vibrational-rotational transition from state (001) $\Rightarrow$ (100), only the P-branch is shown i.e. for $\Delta j = -1$

As the state (001) consists of only rotation states with uneven J and the selection rule $\Delta j = -1$ is to be observed for the P-branch, so the transitions succeeds only for the rotation states of the state (100) with even J.
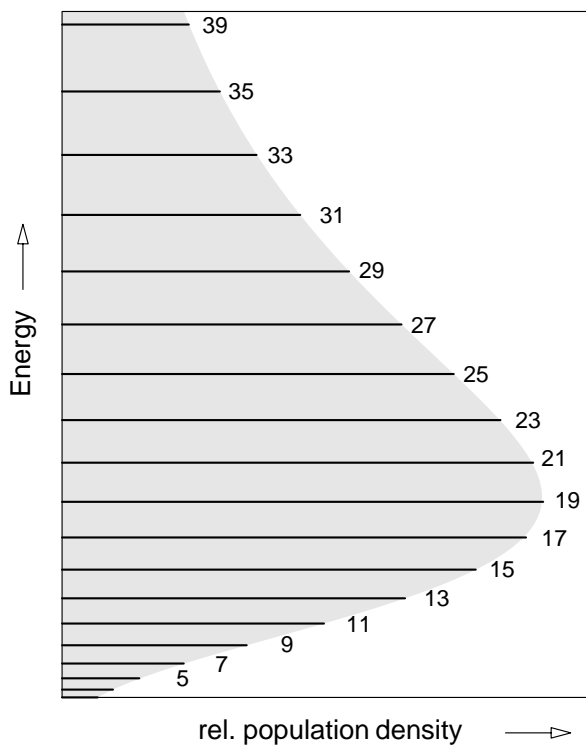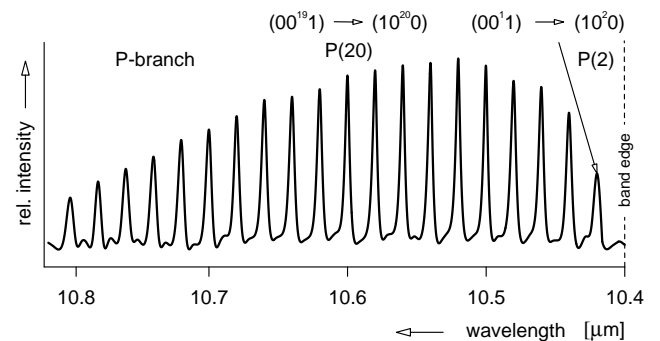

Fig. 16: Uneven rotational level of the (001) vibrational state with a relative population density at 400° K

Such a type of distribution in the rotational state is possible only when an excitation takes place e.g. through electron impact and consequently an appropriate number of

4 Laser process

For a Laser process the following conditions are required:
1. Energy states which can be inverted, i.e. an energetic high lying state excited in such a manner that there are more molecules found in the excited state than in an under lying state.
2. Between both these states, an optical transition must be allowed.
3. There must exist an excitation mechanism with which the upper state can be excited effectively.
4. There must exist a "de-excitation mechanism", so that the molecule reaching the lower state are again at the disposal of the excitation mechanism.
5. For the generation of Laser light an suitable optical resonator is necessary.
6. For the excitation an energy source is needed

Points 1-4 will be dealt with in the following chapter, point 5 in the chapter Gas discharge and point 6 in the chapter Laser resonator.
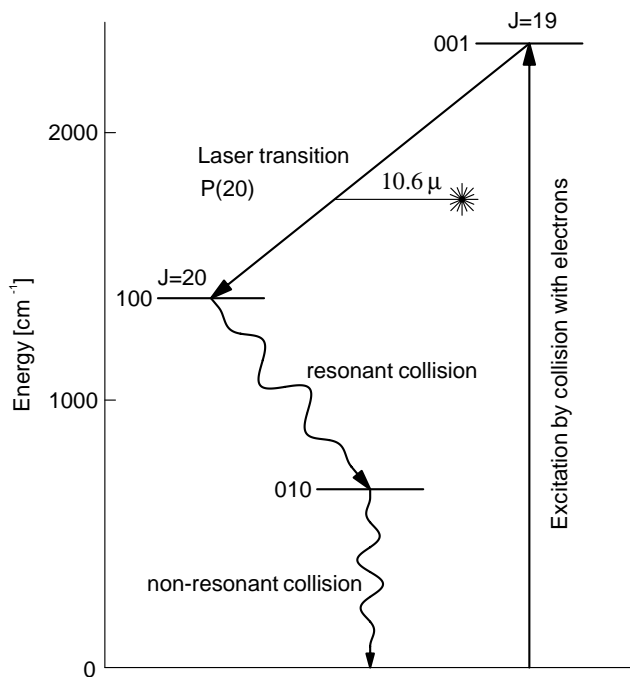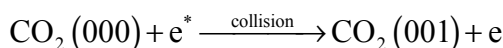

**Fig.18: Laser cycle for the 10.6 μm Laser line**

The excitation of the Laser output level (001) results from the ground state (000) through an electric discharge. There, an electron collides with an molecule of the ground state and excites this to state (001).

$$CO_2\left(000\right)+e^{*}\xrightarrow{\quad collision\quad}CO_2\left(001\right)+e$$

The excitation through an electric discharge is never so selective so as not to also excite the other excitation level of mode $(00v_3)$. Fortunately the energy gap of the vibration level is nearly the same, so that the "very highly excited" molecules through collision with the molecules of the ground state again arrive in the (001) state:

$$CO_2\left(002\right)+CO_2(000)\xrightarrow{\quad collision\quad}2\cdot CO_2\left(001\right)$$
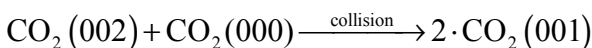
From the level (001) spontaneous emission takes place. Thereafter, the previously excited (001) molecule goes in the state (100):

$$CO_2\left(001\right)\xrightarrow{\quad emission\quad}CO_2\left(100\right)+\text{Photon}$$
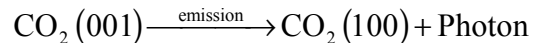
The spontaneous emission is a process, which cannot be influenced through external manipulations. It depends exclusively on the uniqueness of the respective energy state. This process is responsible for the initiation of the Laser oscillation which only can start when an optical resonator is available fulfilling the required conditions. This is explained in detail in the chapter on Laser resonators.

To make the population inversion possible, it must be ensured that the level (100) is emptied again. An optical or radiating transition from (100) to (000) is allowed, though it is relatively weak. A much more effective energy exchange takes place on the near resonant transition:

$$CO_2\left(100\right)+CO_2\left(000\right)\xrightarrow{\quad collision\quad}2\cdot CO_2\left(010\right)$$
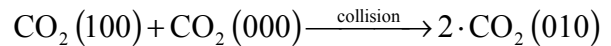
The molecule from the state (100) collides with the molecule from the ground state (000). In the process this molecule collects so much energy that it is excited to the (010) state. The colliding molecule keeps a residual amount of energy which is nearly equivalent of a molecule of the (010) state. In case residual energy is present, it is transferred to existing rotation states. Now it is necessary to take the last hurdle to the ground state. If it does not come to this step, then there would be no molecule available which could be excited to the (001) state. This last step in fact, represents the "bottle-neck" of the whole cycle and can only be achieved through collision with the wall of the discharge chamber, because it is the lowest level before the ground level and radiating transitions are not permitted.

$$CO_2\left(010\right)\xrightarrow{\quad wall\ collision\quad}CO_2\left(000\right)+\Delta E$$
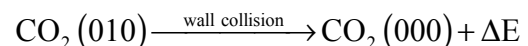
In such a situation one looks for an appropriate collision partner who supportingly accelerates this last step. But on no account should such a partner unfavourably influence the remaining cycle, and it should also not have any chemical reaction with the CO_2. Here the inert gases always offer their services. In fact He has proved to be such a partner. Through an admixture of Helium in CO_2 gas, this bottle-neck can be removed. However, there is an unwritten law for the preservation of the bottle-neck; hardly a bottle-neck is removed from one state and a new one's occurrence is guaranteed at another place. So here too, the bottle-neck is the present excitation mechanism. To improve upon this i.e., to make it selective, one uses a homonucleus molecule, nitrogen. The fact that the first excited vibrational level of the N_2 lies under the dense energetic state (001) of the CO_2 is an established co-incidence. The energy difference amounts to only 18 cm^{-1}.
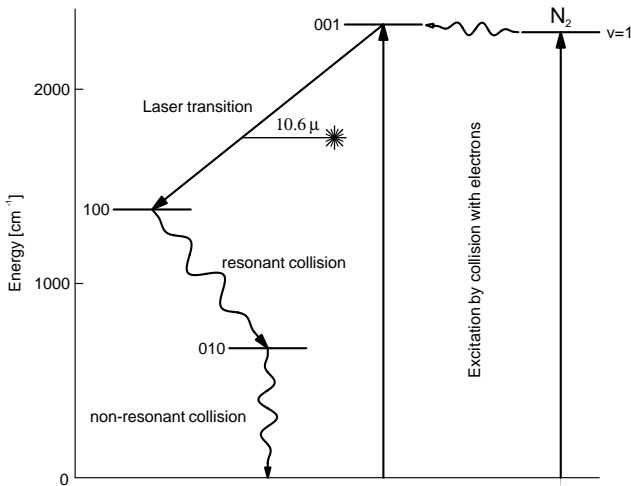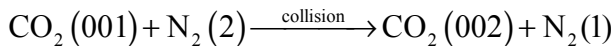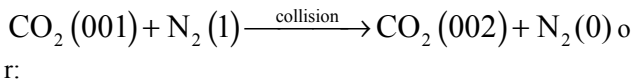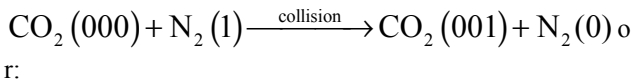
Fig.19: N_2 for the improvement of the excitation

With the introduction of nitrogen into the existing mixture of CO_2 and He, the power output of the CO_2 Laser improves by around 20%. Since nitrogen is a homo-nuclear molecule, the transition within an electronic state is not possible. That is why the most probable relaxation mechanism is of collision with a CO_2 molecule, by which the vibrational energy of N_2 is transferred to the resonance of the CO_2 molecule. When the already excited CO_2 molecules undergoing such a collision, they are transferred to the next level of the vibration ladder, but subsequently collision with molecules of the ground state the (001) state is filled again.

$$CO_2(000) + N_2(1) \xrightarrow{\text{collision}} CO_2(001) + N_2(0)$$

or:

$$CO_2(001) + N_2(1) \xrightarrow{\text{collision}} CO_2(002) + N_2(0)$$

or:

$$CO_2(001) + N_2(2) \xrightarrow{\text{collision}} CO_2(002) + N_2(1)$$

Since in the N_2 molecule too, the energetic differences of the vibration level with lower values for v are likewise equidistant, a vibration transfer can also take place in higher (00v) states of CO_2 molecules. As seen before, these states, however arrive again in the (001) state. N_2 is therefore an excellent partner for the improvement of excitation selectivity. Typical values for optimum mixing are 4 mbar of CO_2, 4 mbar of N_2 and 27 mbar of He. However, these are still not all the processes which influence Laser efficiency.

Till now we have assumed that the states (100) and (010) are populated by the Laser process and depopulated through collision. However, this level can also be populated through thermal impact because of the temperature of the gas – the higher the temperature, the larger does the thermal population density get too. With that, the inversion between the states (100) and (001) is reduced on one hand and on the other hand the depopulation of the state (010) is diminished. Both effects contribute to the efficiency of the Laser process. The temperature of the Laser gas depends on the strength of the discharge. A higher current dis-

charge correspondingly elevates the temperature, thereby reducing the Laser output power. Therefore, the power limit of the CO_2 Laser is defined by the effectiveness of the cooling of the Laser gas.

A further process is the production of carbon monoxide which originates through the disassociation of CO_2 under the influence of electric discharge. While the CO improves the selectivity on one hand, it causes a reduction in the number of CO_2 molecules on the other. As the discharge takes place in a closed capillary (sealed off Laser), so it is only a matter of time until the CO content dominates and the Laser process comes to a standstill due to a lack of CO_2 molecules.

5 Practical CO$_2$-Laser

The production of the CO_2 Laser with extremely high power outputs, presents the opportunity for intensive research in order to fulfil the requisite features for material processing in sophisticated technical designs. But the number of applications are increasing daily. Now it is important not only to have very high power at ones disposal but also service reliability and at a cost that correspondingly matches its function. Therefore, different technical variations of the CO_2 Laser came into existence. We have learnt in the previous chapter that the maximum attainable power output depends upon the efficiency of excitation and the cooling of the Laser gas.
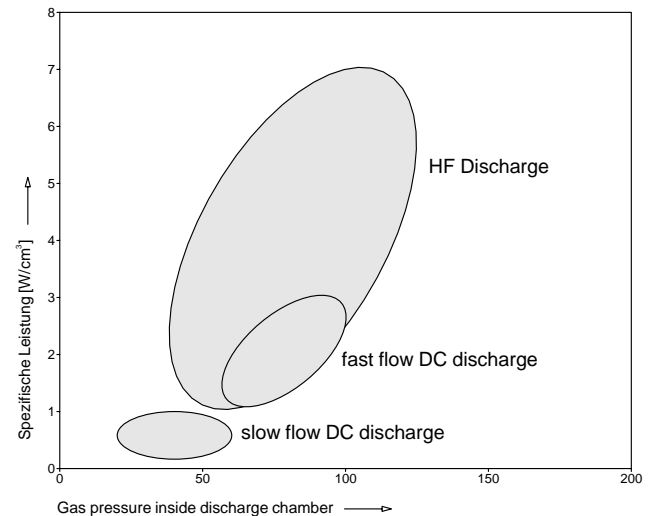

Fig.20: Comparison of the specific power, DC and HF excited CO$_2$ Laser

Thus the practical designs of the Laser vary according to the form of selective excitation, the cooling of the gas and with it the attainable power output. The development of a cost effective power semiconductor for the high frequency region made it possible to realise high frequency excited discharging. They also have the advantage against parallel flow discharge as the power can be connected to the Laser gas almost without losses. To make a comparison among the different systems, the details of attainable Laser power per cm^3 of active volume is used (Fig.20).

Sealed off systems	70 W/m
Slow flow systems	100 W/m
Fast flow systems	800W/m
Pulsed Systems TEA	1.2 TW pulse

Table 2: Different types of CO$_2$ Laser

We use a DC excited slow-flow Laser within the framework of this experiment. Now we shall briefly introduce some other important systems. The description of HF system in not in this framework because on one hand of its continual development and on the other that it is considered as a group of highly optimised systems. Anyway, the basic physical Laser aspects remain common to all systems.

5.1 Sealed off Laser

The scheme of the Laser systems as a whole, at first seems rather simple; but the various details adopted for system longevity are quite complex.
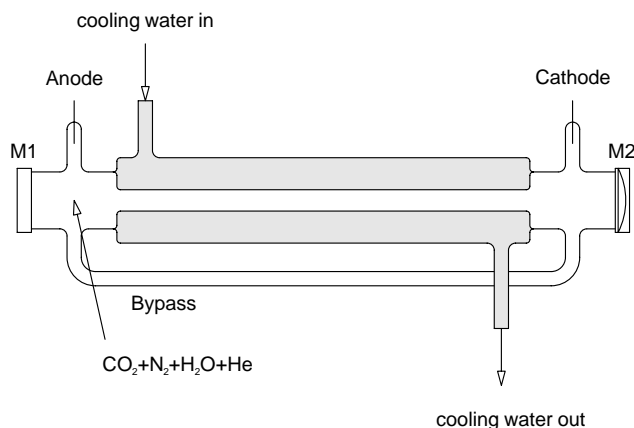

Fig.21: Sealed Off Laser system

The electrodes must be made of a precious metal so that the continual material erosion does not react with the gases and specially with its disassociation products. The addition of water vapour takes care that the formed CO gas re-mixes again with the CO$_2$ gas. Optimised systems achieve power outputs of up to 70 Watt per meter of discharged length. The cooling of gases takes place through diffusion-that means that the gas molecules diffuse from the centre of the discharge to the wall, where they are cooled by collisions. A bypass prevents the de-mixing of the gases. The example in Fig.21 depicts a convection cooled system.
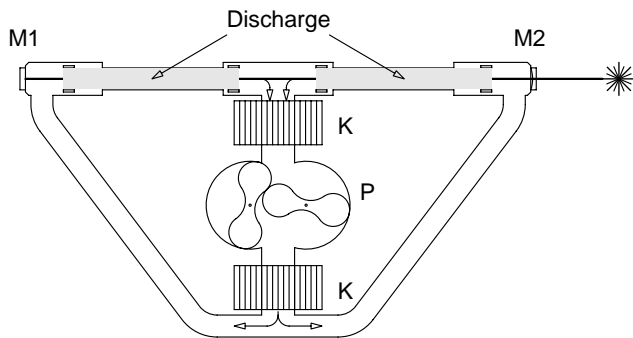
5.2 Fast Flow Laser

Fig.22: Longitudinal excited fast flow system

The hot Laser gas is sucked off from the discharge chamber with the help of a Roots vacuum pump (P). In the process it passes through the heat exchanger (K), into the double step cooling (K). It then passes by the mirrors M1 and M2 and it finally enters the discharge section again. In such systems Laser power up to 2 kW are generated. For Laser powers from 5 kW however, the transversal excitation system of Fig. 23 is more advantageous, because here, due to the far lower electrode distance, the necessary ignition and drop voltage is comparatively low.
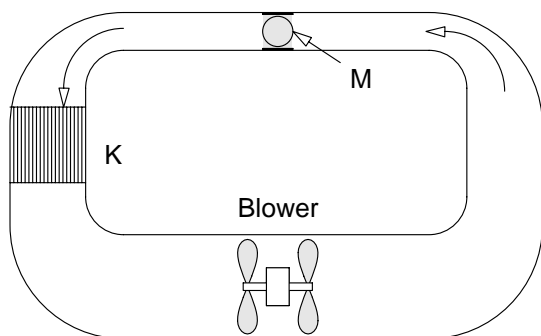

Fig.23: Transversal excited fast flow system

In this design, the Laser gas is guided squarely across the discharge chamber and the resonator with the mirror M. The gas transport is achieved by the blower drawing the hot Laser gas into the heat exchanger K for cooling.

5.3 Pulsed CO_2 Laser

A separate class of CO_2 Laser represents the pulsed system. The system present till now can be pulsed only by tuning the electric discharge. Due to the high life time of the Laser output level (001) from 1 msec, a switching technique is also possible for the production of higher peak power. However, this technique did not go further because the electrooptical switch for the wavelength of 10.6 μm was not available with the required high damage threshold. It was and is in fact easier, to select a powerful Laser system and to pulse a discharge. The development of a pulsed CO_2 Laser formed the basis of a third way to solve the problem of heat disposal of the Laser gas, namely through the utilisation of the specific heat of the

Laser gas. Up to now, this was realised through convection and diffusion. This new concept, that essentially more molecules should be available makes sense. This means that the pressure in the discharge system has to be increased. This eliminates the continuos operation, because through the increased number of collisions, inversion is destroyed. However, it the excitation pulse is faster than the destruction of inversion, then a Laser pulse can be generated whose time constant depends on the mechanisms time constant. Laser systems designed of this type are called TEA-Laser, where TEA stands for Transversal Excited Atmosphere, meaning that this Laser is operated by atmospheric pressure. Lasers of this type have hardly any technical use but are used in big research plants under extremely high peak power to examine the nature of matter. A superlative CO_2 Laser system by the name DBM was built in the scientific laboratory in Los Alamos. It has shown the following characteristics:

Life time of inversion	4 μsec
Duration of exciting pulse	3 μsec
Laser pulse width	1 nsec
Beam diameter	15 cm (!)
Peak power	15 TW

After this review of different CO_2 Laser types, we now return to the slow flow Laser which is used in this experiment.

5.4 Slow Flow Laser

Nothing essentially more is required to be added to the fundamental properties of a system like this as all its aspects have already been explained in the previous chapters. These are or were the systems of the early years of development. For experimentation, this system is ideal with regard to Laser behaviour and material processing capabilities.
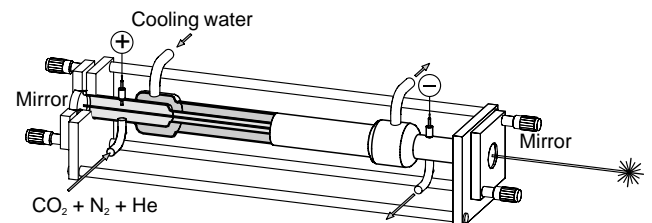

Fig.24: Longitudinal excited slow flow System

With an optimised system having an excitation length of 1 meter, Laser power of up to a maximum of 100 Watt can be achieved. The excitation takes place over a longitudinal direct current discharge, which shall be closely discussed, in the following chapter.

6 Gas discharge

As already mentioned the excitation of the Laser output level takes place through the collision of CO_2 molecules with electrons of suitable energy. These are produced in a discharge length. In general, discharge length is a capillary

whose diameter is selected on one hand to be so small that relaxation through the wall collision is the highest possible but on the other hand it has a sufficiently large diameter so that the Laser beam does not suffer any loss through vignetting. In the most simple case, at the ends of the capillary, electrodes are attached which carry a high voltage.
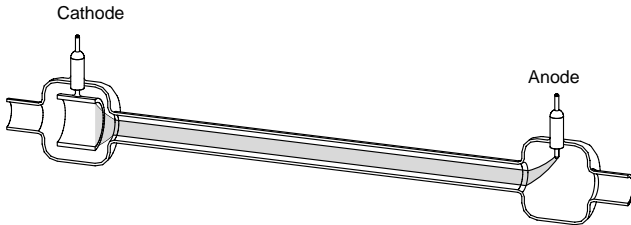

Fig.25: Discharge tube with ring cathode

When the electrodes carry a high DC voltage (about 1000 volts) then the free charge carrier are accelerated in the direction of the corresponding cathode or anode depending on their polarity. Although the gases used in our case do not posses an outside charge themselves, there still always exist free electrons and ions which are generated through unavoidable external ionisation like natural atmospheric radioactivity or cosmic radiation. The ions generated thus, under the influence of high field intensity hit the cathode, recombine there, and release electrons on the other hand, which ionise further molecules or atoms on the way to the anode. In this manner, the number of free charge carriers increases continuously and a current starts to flow.

If the voltage is high enough then the independent discharge starts. This is characterised by the electron leaving the cathode producing so many ions that they generate an electron in the cathode in turn. Ionisation takes place along the whole discharge length and a fluorescent light typical for the atoms or molecules is observed. The electrons reaching the anodes invade the anode material and become power electrodes. The fact that the voltage necessary for the flow of current becomes low by the rising current is typical for a gas discharge.
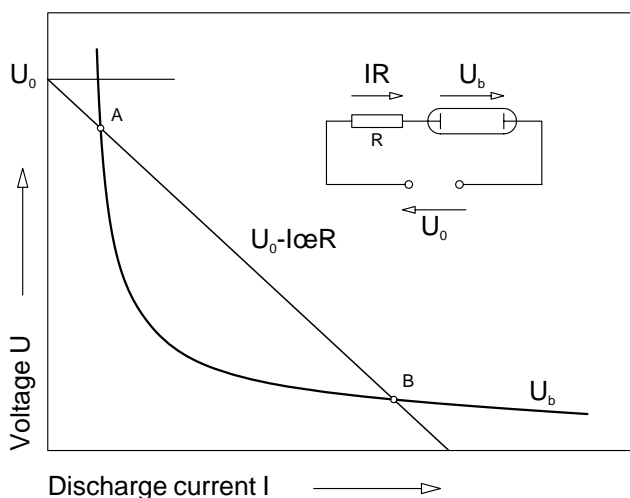

Fig. 26: Voltage and current characteristic curves for a gas discharge

If no measures are taken, the current shall increase like an avalanche, so far as permitted by the current source and then the discharge length turns into a plasma state whereby almost all the molecules and atoms are repeatedly ionised. But this is not our aim, because we need a fixed energy of electrons for efficient excitation. To achieve this a resistance in series is attached to the discharge length. A rising discharging current I produces a steep voltage drop at resistance R, thus leading to a reduction of voltage at the discharge length.

The resistance is chosen in such a way that it results in at least one or even better two points of intersection (A,B) With this the discharge current is limited and the voltage U_b is adjusted in the discharge tube. This classical solution has a clear disadvantage, because an important part of the electrical energy is lost at the resistance as heat loss. However, by means of modern electronics this disadvantage can be reduced to the minimum. For the adjustment of discharge current a variable stabilised current source is used.

7 Types of resonators

The most simple optical resonator, the Fabry-Perot resonator, consists of a pair of plane or spherical mirrors located opposite one another. They are centred to a common optical axis and are aligned perpendicular to this axis
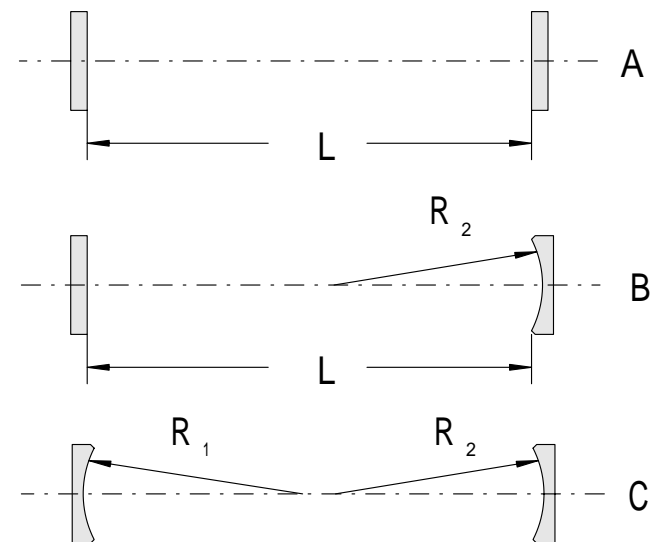

Fig. 27: Types of resonator

There are basically three different types of optical resonators:

plane parallel resonator	**A**
hemispherical resonator	**B**
spherical resonator	**C**

For Lasers in the low to medium power range (1 mW-200W), the hemispherical resonator is mainly used. Its features include high output powers with relatively uncritical mechanical adjustment. Apart from other parameters, the output power depends on how much of the Laser-active material is used. In this respect the terms pump vol-

ume and mode volume are used. The pump volume is the volume of the active material which is illuminated by the pump radiation. In contrast the mode volume is the volume which the Laser modes fill within the Laser-active material. By selecting the focusing, the pump radiation and the resonator shape the designer can influence both quantities. In the optimum case the pump volume should be a little larger than the mode volume. The mode volume depends on which beam parameters are chosen within the Laser resonator. These parameters are determined by the selection of the type of resonator , the radius R of curvature and separation L of the mirrors. However, it should be noted that within certain limits the separation L of the mirrors cannot be varied at will for a given radius R of curvature.

7.1 Stability criterion

The range in which a resonator configuration exhibits any kind of optical stability is found by the stability criterion. A resonator is optically stable if, after any number of reflections, the light still remains in the resonator due to the imaging characteristics of the mirrors used and does not leave the resonator by protruding beyond the edges of the mirrors. For the plane parallel resonator (A), in which the light beam is only reflected and not modified in shape, it must be ensured that both plane parallel mirrors are adjusted exactly parallel to one another. This type of resonator is the most difficult to adjust and to maintain in a correctly adjusted condition. The spherical resonator (C) is the most simple to adjust, but has the disadvantage that undesired transverse modes can easily start to oscillate. This means that the Laser power is split up over a number of modes which are separated spatially from one another and which cannot be focused to a common point as with longitudinal modes. The hemispherical resonator represents a satisfactory compromise and the stability range for this type of Laser is determined in the following.

In the following section some fundamentals used in the description and calculation of optical resonators will be introduced. Stability diagrams, the beam radius and beam sizes for the resonator types used in later experiments will be calculated and discussed. The investigations and calculations will be carried out for an "empty" resonator since the characteristics of the resonator will be particularly influenced (e.g. thermal lenses, abnormal refractive index etc.). The ABCD law will be introduced and used in this context. Just like the Jones matrix formalism this type of optical calculation is an elegant method of following the beam (ray tracing) in a complex optical system. Fig. 13 shows that an identical lens system can be constructed for every optical resonator. The beam path of the resonator can be traced using the ABCD law, aided by an equivalent lens system. So, how does the ABCD law work ?

First we must presume that the following calculations are correct for the limits of geometric optics, that is if the beam angle is < 15° to the optical axis, close to $\sin\alpha \cong \alpha$. This has been fulfilled in most systems, especially for Laser resonators. A light beam is clearly defined by its height x to the optical axis and the slope at this point (Fig. 14).
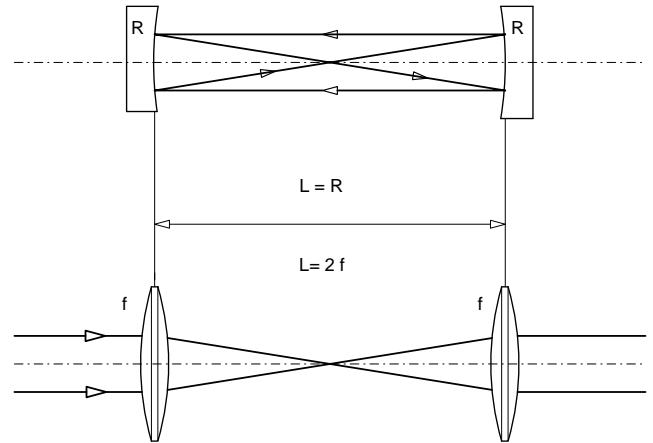

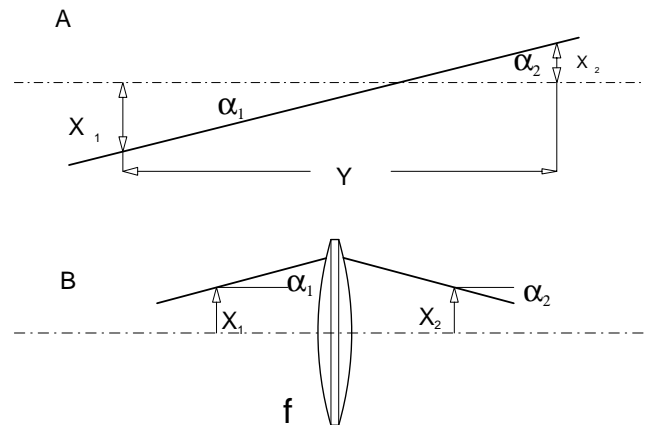**Fig. 28: Spherical resonator with equivalent lens guide**

Fig. 29: A. light beam with the characteristic sizes. B. Trace through a lens.

The matrix to be introduced is called the beam transfer matrix or ABCD matrix. When this matrix is applied to the input quantities x_1 and α_1 the resulting output quantities will be x_2 and α_2:

$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

Example A in Fig. 29 shows the free propagation of a beam, from which we can deduce that

$$\alpha_1 = \alpha_2 \text{ and } x_2 = x_1 + \alpha_1 y.$$

So, the ABCD matrix in this case is:

$$A = \begin{pmatrix} 1 & y \\ 0 & 1 \end{pmatrix}$$

In example B which shows a thin lens the matrix is:

$$B = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

It is easy to understand that the combination of example A and B is a result of free beam propagation with subsequent focusing with a thin lens

$$X_2 = A \cdot B \cdot X_1$$

A series of ABCD matrices for different optical elements can be drawn out with this method. They have been compiled by Kogelnik and Li [3]. The above examples are sufficient for the calculation of a resonator. Beams in an optical resonator have to pass through the same optical structure several times. After passing through it n times the ABCD law for a particular place Z of the lens guide (Fig. 13) would be:

$$\begin{pmatrix} x_f \\ \alpha_f \end{pmatrix}^n = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^n \cdot \begin{pmatrix} x_i \\ \alpha_i \end{pmatrix}$$

In this case the ABCD matrix is the identical lens guide given to the resonator. The n-th power of a 2 x 2 matrix is calculated as follows:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^n = \frac{1}{\sin(\theta)} \cdot \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

$$a = A \cdot \sin(n\theta) - \sin((n-1) \cdot \theta)$$
$$b = B \cdot \sin(n\theta)$$
$$c = C \cdot \sin(n\theta)$$
$$d = D \cdot \sin(n\theta) - \sin((n-1) \cdot \theta)$$
$$\theta = \arccos\left(\frac{A+D}{2}\right)$$

The trace of the above ABCD matrix |A+D| must be ≤ 1 if the beams are to remain within the lens guide. So,

$$\boxed{|A + D| \leq 1 \qquad \textbf{Eq. 8}}$$

This is now the criteria of stability for the lens guide and therefore also for the accompanying resonator. Considering that the focal length of a mirror is given by R/2 where R is its radius of curvature and with L as distance of two mirrors on obtains the relation for the g-parameter:

$$g_i = 1 - \frac{L}{R_i} \qquad \textbf{g - Parameter}$$

L is the mirror separation and R is the radius of curvature of the Laser mirror. The index i is 1 for the left mirror and 2 for the mirror on the right side. If the product $g_1 g_2$ satisfies the condition

$$0 \leq g_1 \cdot g_2 \leq 1 \qquad \textbf{stability criterion}$$

then the resonator is optically stable and the light, once

produced, does not leave the resonator by passing over the edges of the mirror. Instead the light remains within an upper limit referred to a distance parallel to the optical axis of the resonator. The stability diagram for the case of interest here is shown in Fig. 30 for the hemispherical resonator.
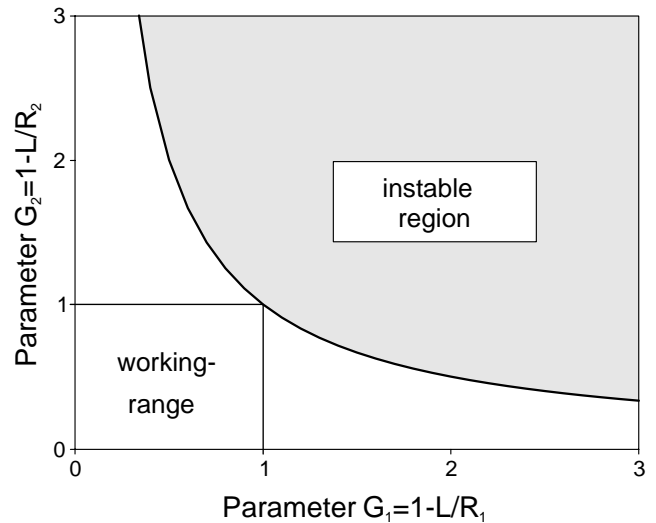

Fig. 30: Stability diagram

For this resonator $g_1=1$, since $R_1 = \infty$ (plane mirror). All resonators are unstable above the limiting curve $g_1 g_2 = 1$ and are stable below this limit. Since $g_1 = 1$, then with a fixed R_2 the distance of mirror 2 can only be changed from $L=0$ ($g_2 = 1$) to $L=R_2$ ($g_2 = 0$). The distance that is actually adjusted within this range depends on the application for which the Laser is to be optimised for. The closer the resonator is operated to the stability limit, then the more sensitive it is to maladjustment, because even small changes in separation can take the resonator into the unstable region (e.g. thermal expansion). The mirror separation can be decreased to prevent this problem, but the mode volume is reduced and this in turn significantly affects the output power of the Laser.

The optical resonator of the CO_2 Laser is designed according to the given active material and the required beam quality. The objective is to achieve the best possible beam output in the basic Gaussian mode (TEM_{00}). Generally speaking these are two contradictory requirements since a high power output requires the use of a large volume of the active material, whereas the fundamental mode is restricted to its own volume. This is why the hemispherical resonator has the optimal configuration for the CO_2 Laser. This can be explained by the characteristics of Gaussian beams. The beam radius w (w = waist) is a result of the following relationship:

$$w(z) = w_0 \cdot \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

w_0 is the smallest beam radius at the minimum of the beam waist and z_R is the Rayleigh length.

$$z_R = \pi \cdot \frac{w_0^2}{\lambda}$$

Fig. 31 shows the relationship between the beam diameter and the length z pointing into the direction in which the beam is propagating.
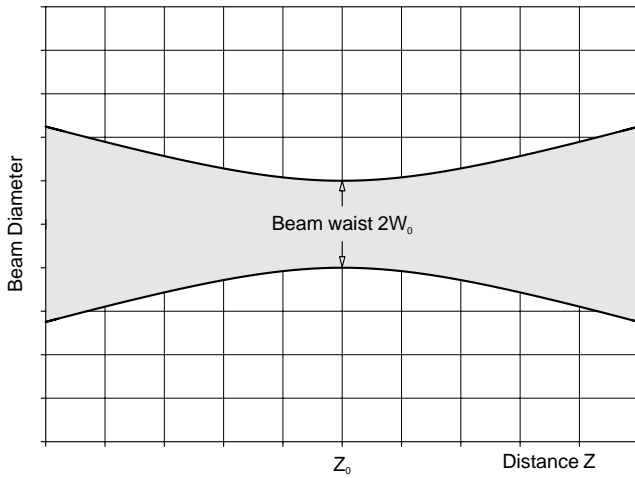

Fig. 31 The beam diameter of a Gaussian beam in the fundamental mode

The beam's radius is smallest at the location z_0. The beam radius increases in a linear form as the distance increases. Since light waves are spherical waves a radius of curvature of the wave front can be allocated to each location z. The radius of curvature R(z) can be calculated with the following relationship:
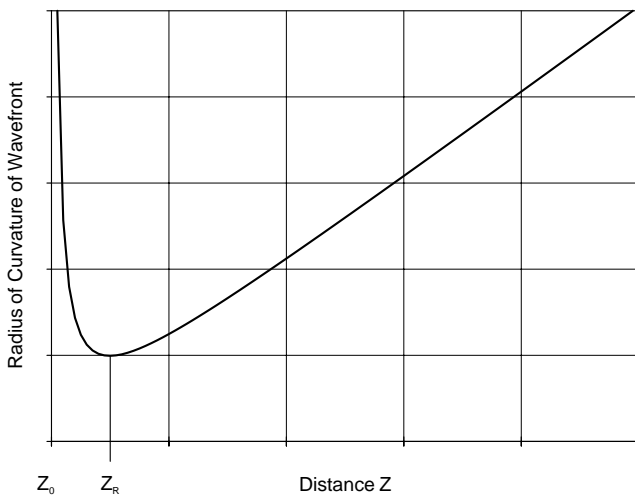
$$R(z) = z + \frac{z_R^2}{z}$$

as illustrated in Fig. 32

Fig. 32: Radius of curvature of the wave front versus the distance z from the beam waist at z=0

At $z = z_R$ the radius of curvature is at a minimum and increases at l/z against zero. The radius of curvature at z=0 is infinite. At this point the wave front is plane.
Above the Rayleigh length z_R the radius again increases in linear fashion. This is a basic but important statement. It shows that there is a real parallel beam at only one point of the light wave, that is at its focal point. In the range

$$-z_R \leq z \leq z_R$$

a beam can be considered as parallel or collimated. Fig. 33 shows the Rayleigh range as well as the divergence angle θ for the far field.
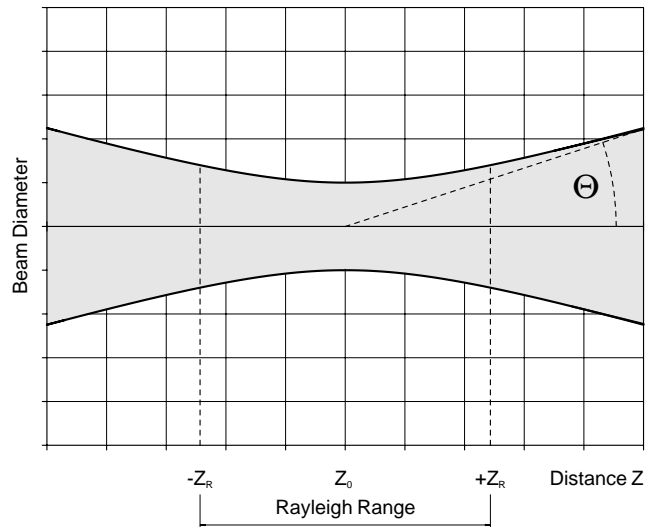

Fig. 33: Rayleigh range and divergence

When reversing the operation a stable optical resonator can now be constructed by adapting the radii of curvature in such a way that they correspond to the radii of curvature of the basic Gaussian mode (Fig. 34).
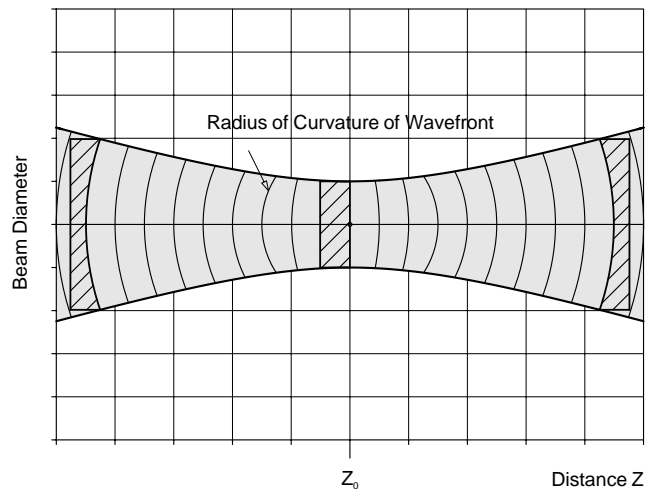

Fig. 34: Construction of an optical resonator with mirrors. The resonator has the same radii of curvature as the fundamental Gaussian mode has at particular points of z
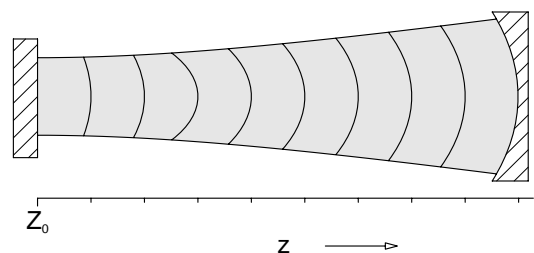

Fig.35: As Fig. 34 but for a hemispherical type of resonator

7.2 Resonator modes
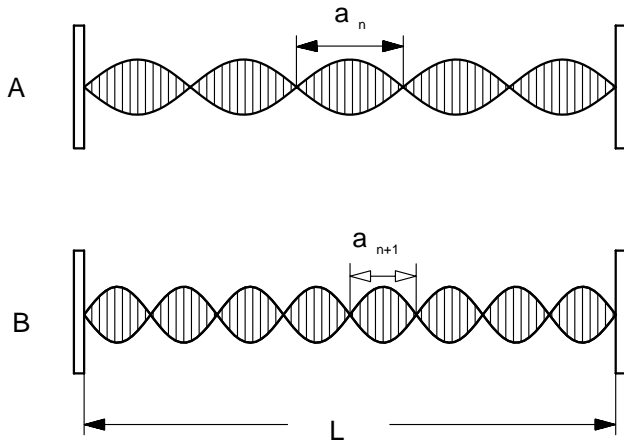
7.2.1 Longitudinal modes

Fig. 36: Standing waves in a resonator with plane parallel mirrors. In the upper example five longitudinal modes fit into the resonator of length L and in the lower one n=8

The light wave is reflected at the mirrors and returns along the same path. The electric field strength of the wave is therefore zero at the mirrors. For a certain separation L of the mirrors only waves can be formed which have a field strength of zero at both mirrors. Obviously, this is possible for a large number of waves for which an integer number n of their half wavelengths $\lambda/2$ fit in the resonator. The waves which fit into the resonator are termed oscillating modes or simply modes. If this integer number is n, then all waves fit into the resonator for which

$$n \cdot a_n = L$$

is true. The next neighbouring mode fulfils the condition

$$(n+1) \cdot a_{n+1} = L$$

The separation between the wavelength of two neighbouring modes is $2a_{n+1} - 2a_n$. If λ is the wavelength, ν the frequency and c the velocity of the wave, then the following applies with:

$$a_n = \frac{\lambda_n}{2} \text{ and } \nu = \frac{c}{\lambda}$$

$$\left|\delta\lambda\right| = \left|\lambda_{a(n+1)} - \lambda_{a(n)}\right| = \frac{2 \cdot L}{n \cdot (n+1)}$$

or:

$$\delta\nu = \frac{c}{2 \cdot L}$$

The magnitude of $\delta\nu$ is termed the mode spacing. For a resonator with a length L of e.g. 50 mm, the mode spacing $\delta\nu$ amounts to 3 GHz. In principle there are a very large number of modes which can fit into the resonator. However, the Laser-active material can only amplify a certain limited range of these modes. For the CO_2 Laser the wave-

length at which the maximum gain occurs is 10.6 μm or at a frequency of $2.8 \cdot 10^{13}$ Hz. The region in which amplification takes place is given by the gain bandwidth $\Delta\nu$.

$$\Delta\nu_{p,T} = C(\alpha) \cdot p \cdot \left(\frac{300}{T}\right)^{1/2} \text{MHz}$$

$$C(\alpha) = 7.58 \cdot \left(\alpha_{CO_2} + 0.73 \cdot \alpha_{N_2} + 0.64 \cdot \alpha_{HE}\right)$$

Therein T denotes the absolute Temperature, p the total pressure inside the discharge capillary and α for the relative partial pressure of the particular gas. At a partial pressure of

CO_2	0.14
He	0,67
N_2	0,19
Total pressure	50 torr

a gain bandwidth of 232 MHz will be obtained. Therefor one should expect that for a resonator length of 50 cm corresponding to a free spectral range of 300 MHz only one mode should oscillate. Without doubt this is a particular property of the CO_2 Lasers comparing it to the HeNe-Laser with a gain bandwidth of 1.5 GHz. The broadening of the gain bandwidth of a gas Lasers is mainly caused by the so called Doppler broadening. Due to the different velocity of the gas atoms or molecules. A resting molecule (v=0) will emit its resonance frequency of ν_0 while a moving one (v≠0) will emit a Doppler shifted frequency of:

$$\nu = \nu_0 \cdot \left(1 \pm \frac{v}{c}\right)$$

The statistical velocity distribution of gaseous atoms or molecules are represented by the Maxwell-Boltzmann distribution (Fig.37)
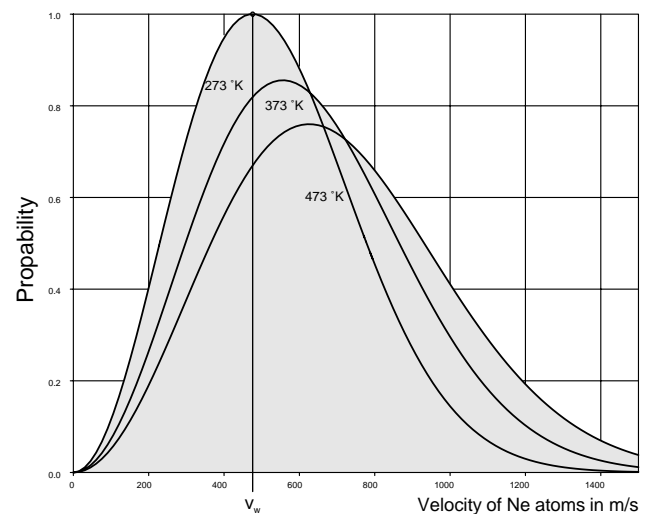

Fig.37: Probability and velocity distribution of freely moving gas molecules or atoms (Maxwell-Boltzmann)

Based on the Doppler broadening the bandwidth of the gain distribution results in:

$$\Delta\nu_D = \frac{2}{\lambda_0} \cdot \sqrt{\frac{2kT}{M} \cdot \ln 2}$$

The letter k denotes the Boltzmann constant, M the reduced mass of the molecule and λ_0 the emission wavelength of the resting molecule. Obviously the gain bandwidth will increase with increasing temperature T and decrease with increasing resonance wavelength λ_0 and mass of the molecules or atoms. Since the wavelength of the CO_2 Lasers is 18 times that of the HeNe-Laser and the mass of the CO_2 molecule significant larger the gain bandwidth will be accordingly smaller. The emission or gain profile resulting from a velocity distribution is also termed as an inhomogeneous broadened profile. A Laser having such a gain profile will oscillate on several longitudinal modes if the resonator length is permitting it. In this case the modes will be fed from different velocity groups and can exist without any interaction independently from each other.

The CO_2 Laser possesses a distinctive feature, although the gain profile is Doppler broadened it appears as homogeneously broadened. This shall be explained in the following.

The excitation of the initial Laser level is achieved firstly by electron collision and secondly due to collisions with excited N_2 molecules. The excitation bandwidth is that broad that instead of only one a large number of rotational states of the (001) level will be populated. During the life time (1 msec) of the excited vibrational state app. 10^7 collisions will take place, changing the rotational states of this level up to the quantum number J=40. At a typical temperature of the Laser gas of 400°K most of the excited molecules are just populating the J=19 rotational state (Fig. 16). For this level the population inversion has a maximum related to the lower lying state (100) so that the Laser process will be start from this level, depleting thereby the population of this state. But due to the high collision rate this state will be immediately filled up again.
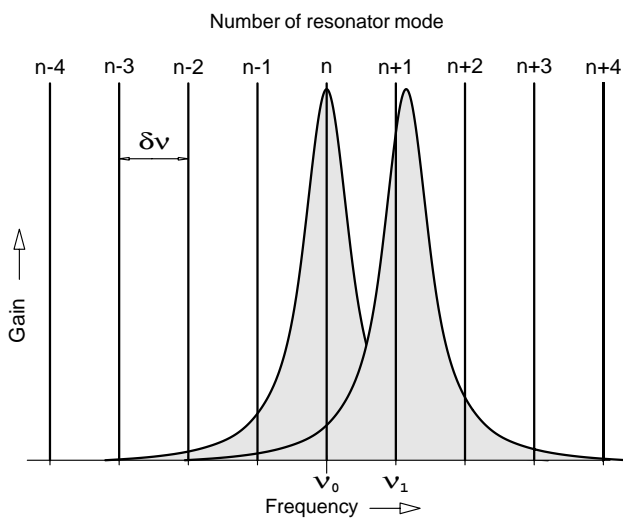
Number of resonator mode

Fig.38: Example of an inhomogeneous gain profile

A Laser system, which emits just one wavelength although the Laser process is fed from different energy levels exhibits a homogeneous gain profile. In case the other rotational

states would not support one major Laser process and initiating their own Laser cycle a lot more wavelength will be generated. Such a gain profile is termed as inhomogeneously broadened (Fig.38).According to the example of Fig.38 the Laser oscillates simultaneously with the frequencies ν_0 and ν_1.

The continuously oscillating CO_2 operates however only on one frequency as explained above. But this is only true if the Laser process will not be disturbed by inhomogeneous gas flow or discharge. In praxis these disturbances cannot completely be avoided so that the CO_2 will although its homogenous gain profile oscillate on different modes or wavelength.

7.2.2 Transverse modes

For the sake of simplicity, the Laser and resonator properties were discussed for an example of a plane parallel resonator. In practice this type of resonator is not used due to its disadvantageous characteristics.
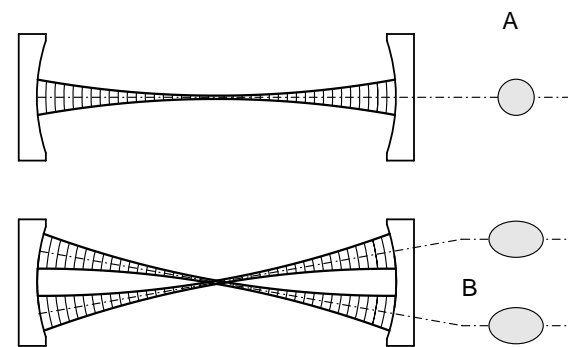
Fig. 39: A spherical resonator with oscillation in the fundamental TEM_{00q} (A) and a transverse mode TEM_{01q} (B)

The hemispherical resonator has become very popular, since it exploits in a special manner the desired mode characteristics of the plane parallel resonator and the advantages of adjustment associated with the spherical resonator. However, a disadvantage accompanies this advantage.

Whereas almost exclusively longitudinal modes excite in the plane parallel resonator, transversal modes can also arise in spherical resonators. This effect is shown in Fig. 39. In contrast to Fig. 36 showing the standing waves in the diagram of the electric field of the Laser beam, here the geometrical shape of the beam within the resonator is illustrated.

When the Laser operates in the steady state, the wavefronts at the mirrors have the same radius of curvature as the mirrors themselves. The situation is drawn in case A in which a radiation field has formed symmetrically about the optical axis.

At the resonator output one can see a round Gaussian shaped intensity distribution. But it is also possible for a radiation field to be set up at an angle to the resonator's optical axis. In principle a multitude of this type of radiation field can develop, because in all of these cases the radius of curvature for the radiation field at the mirrors is the same as that of the mirrors. At the resonator output one can now observe intensity distributions spatially separated

and no longer symmetrical about the axis of radiation. Since these modes do not oscillate in the direction of the optical axis (longitudinal) but are mainly transversal, these modes are termed transversal modes. Owing to the large number of modes, a convention has been adopted in which the relevant modes are given a universal designation:

$$T E M_{m n q}$$

TEM stands for **T**ransverse **E**lectromagnetic **M**odes. The indices m, n and q are integer numbers which state the number of intensity spots minus one in the X axis (m) and the number in the Y axis (n) which are observed. The basis for this consideration is the fundamental mode TEM_{00q} which produces just a round spot. In the example in Fig. 39 (B) the designation is:

$$TEM_{01q}$$

The number q states how many nodal points the standing wave in the resonator has. This number does not have any significance for the user of the Laser and is therefore generally omitted.